MIND OVER MATTER: ACCESS TO KNOWLEDGE AND THE BRITISH INDUSTRIAL REVOLUTION

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Declaration

I certify that the thesis I have presented for examination for the PhD degree of the London School of Economics and Political Science is solely my own work.

This thesis consists of 80,873 words.

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Abstract

This thesis argues that the British Industrial Revolution, which marked the beginning of sustained modern economic growth, was facilitated by the blossoming in eighteenth and early nineteenth century Britain of the world's first infrastructure for commercial R&D, composed of a network of 'Knowledge Access Institutions' (KAIs): scientific societies, 'mechanics institutes', public libraries, masonic lodges and other organisations. This infrastructure lowered the cost of access to knowledge for scientists, inventors and entrepreneurs, raising the productivity of R&D and encouraging a sustained increase in R&D effort. This contributed to the acceleration in technological innovation that lay behind the transition to modern economic growth. First, I define the concept of KAIs and explain how they affected the rate of economic growth. Second, I present detailed data on the KAI infrastructure and estimate its effect on the rate of technological innovation during the British Industrial Revolution, using newly constructed spatial datasets on British patents between 1700 and 1852 and exhibits at the Great Exhibition of 1851. Third, I argue that KAIs were largely exogenous to industrialisation, rooted instead in the intellectual developments of the Scientific Revolution and European Enlightenment. Fourth, I show that the prevalence of Knowledge Access Institutions was correlated with the emergence of modern economic growth across countries in the late nineteenth century and that the cost of access to knowledge was a binding constraint to economic progress shared by many countries during this period. Finally, based on the case of late nineteenth century US manufacturing, I investigate the extent to which the emergence of modern economic growth depended on the incentives to innovate rather than the capabilities lent by access to knowledge and other factors. The thesis suggests that the sharp fall in the cost of access to knowledge that we are currently experiencing may give rise to an acceleration in the rate of technological innovation in the coming decades and that policymakers should direct some effort towards mitigating the potentially harmful effects of rapid technological change.

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Introduction

Access to Knowledge and the British Industrial Revolution

The British Industrial Revolution marked the beginning of the age of sustained modern economic growth and an end to the fits and starts of economic progress that had characterised previous eras. The result has been an improvement in living standards in much of the world that would have been all but unimaginable to our forefathers. Deidre McCloskey summarises the contrast in income levels before and after the British Industrial Revolution. Since time immemorial until around 1800, world income per capita fluctuated between about one and five US dollars a day[1]. Since 1800, however, world income per capita has exploded to about sixty dollars a day and to well over one hundred dollars a day in the most advanced economies (McCloskey 2010). Moreover, these figures are likely to significantly under-represent the improvement in the standard of living.[2] The coinciding acceleration in the growth of the variety and quality of the goods and services available to us means that the ratio of consumer surplus to measured output and income is likely to have increased markedly. Furthermore, the additional welfare gains achieved during the past century through improvements in health and longevity appear to be of a similar magnitude to those from higher incomes (Murphy & Topel 2006). In truth, we are immeasurably better off than our forefathers.

We are better off than them because we know more than they did. And the knowledge that counts is embodied in the technology – the machines, materials and medicines – to which we have access. Prior to the British Industrial Revolution, the rate of invention and adoption of new technology was slow and sporadic, but since has been rapid and sustained. What happened in Britain during the eighteenth and early nineteenth centuries that gave rise to this turn in human history?

Were eighteenth century British inventors and other technological innovators uniquely capable of accomplishing a technological revolution? Or were they instead particularly well incentivised by economic circumstances, such as high British wages and cheap energy, which may have encouraged the replacement of manpower with machinery (Allen 2009,Wrigley

[1] in 2005 dollars.
[2] as McCloskey acknowledges (McCloskey 2010)

2010), or favourable access to foreign input and consumer markets owing to colonialism (Pomeranz 2000)?

This is an important question, not just because of the historical significance of the British Industrial Revolution as a turning point in living standards. Rather, a thorough understanding of the British Industrial Revolution might provide useful lessons from which to draw for the management of economies today. Two and a half centuries since the British Industrial Revolution began, a significant proportion of the world's population remains no better off than the average Briton was in the mid-eighteenth century. Clearly, any successful escape from poverty in the interim might still provide us with useful insights for development (Temin 2014).

Furthermore, the prospects for technological innovation in rich countries today are contentious. Robert Gordon has argued that the world technological frontier faces numerous headwinds during the coming decades that might reduce the trend rate of economic growth to its slowest pace since the eve of the British Industrial Revolution itself (Gordon 2016). If this warning is correct then we urgently need to know which headwinds we most need to counter, and to be aware of any tailwinds that we can influence too. If human and social capabilities ushered in the age of modern economic growth in eighteenth century Britain, then we should commit resources to their modern analogues today where they are found wanting, in rich and poor countries alike. On the other hand, if the incentive to innovate was decisive then we need to ensure that this incentive, as fostered by institutions and policies, is alive and well today.

In the debate concerning the causes of the British Industrial Revolution, human and social capability-based arguments have been somewhat played down[3]. This is partly because the basic measures of human capital upon which economists tend to focus, such as literacy and schooling, do not paint eighteenth century Britain in an exceptional light (Mitch 1999). Indeed, the relationship between human capital and economic growth during the British Industrial Revolution appears to have been quite unusual in the context of the overall two hundred and fifty-year record of modern economic growth since (Becker, Hornung & Woessmann 2011). In the global cross-section of countries and sub-regions today, the level of economic development so far achieved is strongly correlated with the current level of human capital in

[3] See Temin (2014) who draws development lessons based on the British Industrial Revolution.

the workforce, as measured by average years of schooling (Gennaioli et al. 2013). Yet, as Joel Mokyr has put it, “Much of the ingenuity of engineers and inventors of the British Industrial Revolution was devoted to reducing the need of workers to be educated and skilled” (Mokyr 2006).

As such, Mokyr has spearheaded a research agenda that focuses on more nuanced concepts of human capital and other social capabilities that are intended to capture the knowledge, skills and societal characteristics that determined the supply of technological innovation during the British Industrial Revolution (Mokyr 2002, 2005, 2009, Meisenzahl & Mokyr 2012, Kelly, Mokyr & O’Grada 2014). In this spirit, this thesis argues in favour of Britain’s capabilities as a proximate cause of the British Industrial Revolution.

Knowledge Access Institutions and the British Industrial Revolution

Nicholas Crafts’ estimates of the quantitative dimensions of the British Industrial Revolution provide us with two important clues as to its underlying causes. First, Britain’s transition to modern economic growth was *gradual*. Second, the rate of growth achieved at the apex of the British Industrial Revolution was slow compared to the rate achieved at the technological frontier during the twentieth century (Crafts 1995, 1996). In the light of these facts, this thesis argues that the blossoming in eighteenth and early nineteenth century Britain of the world’s first substantial infrastructure for research and development (R&D) has an important role to play in explaining the British Industrial Revolution.

This infrastructure was composed of a system of ‘Knowledge Access Institutions’ (KAIs) – learned societies, ‘mechanics institutes’, masonic lodges and public libraries, among other organisations – which over the course of the eighteenth and early nineteenth centuries steadily reduced the cost of access to useful knowledge for the natural philosophers, inventors and technological entrepreneurs engaged in the process of technological innovation. In so doing, KAIs gradually raised the productivity of R&D in the British economy, which in turn also raised the equilibrium supply of R&D effort. These two effects contributed to the gradual acceleration in economic growth that characterised the British Industrial Revolution.

How did KAIs reduce the cost of access to knowledge? There were two main mechanisms. First, through their impact on the culture within eighteenth century British industry they encouraged and facilitated the application of the scientific method, the norms of science and even a little bit of scientific knowledge itself to the R&D process in the British economy (Musson & Robinson 1968, Jacob 1997, 2014, Mokyr 2002, Jacob and Stewart 2004). This resulted in the acceleration of the growth of the knowledge base upon which society could collectively draw to invent new technology (Mokyr 2002). Second, given this knowledge base, KAIs, as a networked system spanning the country and connected to similar scientific institutions abroad, reduced the cost to inventors and technological entrepreneurs of searching for knowledge within the scientific and technological community[4]. Furthermore, by underpinning a connected community of science, technology and entrepreneurship, KAIs raised the level of social capital within the innovation process, aiding the commercialisation of knowledge[5].

To take a celebrated example, the famous Lunar Society in Birmingham facilitated the transmission of knowledge and cemented the personal relationships that enabled James Watt to commercialise his ideas for the improved efficiency of steam engines (Schofield 1963). What has not been fully appreciated, however, is that as the British Industrial Revolution progressed, each successive generation of inventors following in Watt's footsteps and their business collaborators operated within a richer institutional infrastructure and associated culture for innovation than the generation before, providing better access to specialised knowledge and contacts. This raised the productivity of innovators and, in turn, greater encouraged their efforts.

Nevertheless, Britain's eighteenth and nineteenth century KAIs were quite basic relative to the innovation systems that were established in advanced economies during the twentieth century. When countries adopted large-scale corporate R&D departments, research universities and government research bodies[6] – which enabled a much finer division of labour in the search for knowledge, a wider set of solutions to profit-appropriation problems and much greater capacity to finance research – they experienced faster rates of economic growth than Britain did during the Industrial Revolution. Thus, while Britain's KAIs can help explain the emergence of modern economic growth, their shortcomings can also help explain why growth

[4] See Jackson (2010) for a textbook treatment of the effects of networks on economic activity, including communication costs and the diffusion of information.
[5] See, for example, Dasgupta (2005) for an introduction to the economics of social capital.
[6] See Nelson (1993) for an overview of the components of the 'national innovation system'.

during British Industrial Revolution remained moderate by twentieth century standards. The frontier of economic growth in the nineteenth century advanced at an intermediate pace relative to the two eras that it divided. This is because the engine that powered it was the prototype.

Why Britain Built its Knowledge Access Institutions: The 'Enlightenment Subsidy'

Who built Britain's Knowledge Access Institutions and why? Were KAIs simply a response to the British Industrial Revolution? As such, would it be incorrect to describe them as a causal factor in modern economic growth, as opposed to merely a feature? Indeed, the view that the organisations that composed Britain's KAIs were entirely endogenous to the British Industrial Revolution has a rich lineage, dating back, at least, to Marx and Engels (Engels 1895). Nevertheless, I argue against this view on two grounds. First, it is difficult to privately appropriate the social returns to innovation, even when the prevailing legal system protecting intellectual property operates predictably and efficiently and forms of industrial organisation that facilitate the appropriation of returns are feasible. As such, markets tend to do a poor job of incentivising innovative effort, even at the best of times. During the British Industrial Revolution, however, the patent system offered only very expensive and unreliable protection to private inventors (MacLeod 1988) and the large scale 'modern industrial enterprise', which would later facilitate the private appropriation of the returns to technological innovation, was yet to appear (Chandler 1990). As such, it proves difficult to attribute British technological innovation during the Industrial Revolution to endogenous factors alone (Crafts 1995). As KAIs were complements to innovative effort, it follows that it is also difficult to attribute their growth to endogenous demand generated by the Industrial Revolution.

Second, as testimony to the shortcomings of the market, the rapid technological progress within the frontier economies since World War II has been achieved with a great deal of help from government subsidies (Mazzucatto 2011). During the British Industrial Revolution, however, the government provided very little subsidy to innovation, which presents us with a puzzle: since Britain built its KAIs without the help of the state, how did it solve the problem of the 'tragedy of the knowledge commons'? The basic answer is that Britain's eighteenth and nineteenth century KAIs were predominantly financed by private membership subscriptions and donations. But what was it about eighteenth and nineteenth century Britain that made hundreds of thousands of individuals feel that these subscriptions were worth paying when no such revealed preference for the services of KAIs had existed in earlier eras, nor existed in most of Britain's contemporaries?

The answer to this deeper question is that there were many non-profit related motives in eighteenth and early nineteenth century Britain to engage with science and pay KAI subscriptions, which were associated with the ideology and tastes of a society 'electrified' by the European Enlightenment. During the Enlightenment, science acted as the object of Baconian ideology concerning the promotion of the public good, a form of entertainment, a social status symbol, a political pawn and religious inspiration. The demand for science created by these ideological and cultural utilities made a career in science pay and KAIs viable in eighteenth and nineteenth century Britain. While technological innovation during the twentieth century was subsidised by the government, during the British Industrial Revolution it was subsidised by the European Enlightenment.

That said, however, the proliferation of KAIs during the British Industrial Revolution was not due to the Enlightenment alone. KAIs spread because they worked. Physical *phase transitions* between solids, liquids and gases depend on positive feedback mechanisms operating through the interdependent energy levels of molecules. Similarly, the transition from economic stagnation to sustained economic growth during the British Industrial Revolution represented a persistent shift in the state of the economy that is difficult to comprehend without appealing to analogous positive feedback mechanisms. There are various channels through which positive feedback may have operated, such as the cumulative nature of technological breakthroughs (Mokyr 1990) or the growing incentive to invest in human capital as technology became more advanced (Galor & Moav 2004). But another channel may have been the growth of the R&D infrastructure given its interaction with the level of R&D carried out in the economy. KAIs raised the productivity of R&D and as such the amount of R&D undertaken. This in turn raised the economic return to the R&D infrastructure, making its further development profitable, which raised the equilibrium rate of technological innovation further still – and so on into the twentieth century, with the introduction of more capital intensive and effective institutions. Such endogeneity within the economic system is sometimes treated by economists as a problem to be overcome in the search for empirical identification. However, in the case of the emergence of modern economic growth it may be central to the answer.

Knowledge Access and the Rise of Modern Economic Growth in a Global Context

The claim that KAIs facilitated the British Industrial Revolution clearly raises some important associated questions. I aim to address two of the most important of these in the thesis, the first being whether KAIs can help explain the pattern of the emergence of modern economic growth beyond the British case. Certainly, there were KAIs in other countries in the eighteenth and nineteenth centuries and it is possible that they influenced technological innovation there too. Indeed, the countries with significant KAIs infrastructures by the late nineteenth century had generally become members of the 'convergence club' of fast growing economies by 1913, while those without KAIs generally had not experienced modern economic growth by then.[7]

Beyond this basic correlation, however, it is difficult to dig deeper into the relationship between KAIs and the international patterns of the emergence of modern economic growth without doing detailed comparative work. For example, an obvious question to ask is whether Britain assumed industrial leadership in the eighteenth and early nineteenth century because it had more or better KAIs. To answer this question, one would need to assemble an aggregate database of KAIs in comparator countries, but also ask whether Britain's KAIs were different from these in any decisive way. French KAIs were funded and operated by the state rather than by private individuals (Gillespie 1980). Did this affect their efficacy in facilitating modern economic growth? Did the eighteenth century French state tend to direct R&D effort towards sectors and projects that were less impactful on economic growth? Did the state stand in the way of the commercialisation of technology? Or, rather, did privileges awarded by the French government perhaps offer a better appropriation mechanism than the English patent system and the free market?

The comparative work necessary to tackle these questions is beyond the scope of this thesis. However, the thesis does attempt to shed some light indirectly on the cross-country relationship between KAIs and modern economic growth. Since KAIs affected technological innovation by reducing knowledge access costs, examining the sensitivity of technological innovation to national knowledge access costs *per se* as modern economic growth spread

[7] See chapter 6, which provides an international count of publishing KAIs, based on catalogue of scientific publications by Scudder (1877).

internationally during the late nineteenth century, might tell us whether KAIs were operating upon an active global constraint to modern economic growth.

Exploiting variation in knowledge access costs during the late nineteenth and early twentieth centuries due to the global railway transportation revolution suggests that national rates of technological innovation were indeed sensitive to national knowledge access costs during this era. In the three decades before the First World War, the countries in which rail networks were expanded the most experienced faster growth in rates of patenting, a proxy for technological innovation. Moreover, patenting rates were sensitive to the growth of rail passenger volumes not just the growth of rail freight volumes, suggesting that this effect appears to have operated through the reduction of knowledge access costs, as distinct from the improvement in market access to which the rail revolution also gave rise. Furthermore, evidence based on rail and patenting by US states during the decades of the nineteenth century US railway revolution shows that rail raised not only patenting rates but also patent quality. As I explain in the thesis, there are good reasons to believe that this effect on patent quality was due to better knowledge access, as opposed to better market access. As such, the basic cross-country correlation between KAIs and membership of the convergence club may have had a causal dimension.

Weighing Capabilities against Incentives

Finally, as economic outcomes are always determined by the interaction of both supply and demand, the supply-side capabilities for innovation during the British Industrial Revolution, such as those gained due to the KAI infrastructure, should be considered alongside the demand-side incentives. The most prominent argument for incentives as the cause of the British Industrial Revolution is Robert Allen's focus on Britain's high wages and low capital and energy costs, which Allen claims incentivised a self-sustaining cycle of labour-saving technological innovation (Allen 2009). This thesis attempts to measure the importance of Allen's incentives to the emergence of modern economic growth and, as such, to speak to the appropriate balance of emphasis between capabilities and incentives.

To do so, I investigate county-level data on US manufacturing during the late nineteenth century, the period of the American transition to modern economic growth. Because both eighteenth century Britain and nineteenth century America had high wages and cheap energy, which in both cases may have incentivised labour saving technological change, Allen has described the British Industrial Revolution as the 'prequel' to the later American case. While they were distinct events, and no amount of evidence on the American case can speak directly to the British case, the rich data available on the late nineteenth century US manufacturing sector at least enables one to thoroughly test Allen's mechanism while retaining the context of an early experience of the transition to modern economic growth (Abramovitz & David 2001). Was technological change in the late nineteenth century US labour saving? Did rising unit labour costs in US counties prompt faster accumulation of capital per worker? Did higher capital-labour ratios in US counties result in faster rates of labour productivity growth via learning by doing? Was innovative effort sensitive to profitability? On each of these questions, the data provides evidence in favour of Allen's claims, suggesting a substantive influence of incentives on the emergence of modern economic growth. Nevertheless, it also shows that incentives alone cannot plausibly account for the emergence of modern economic growth, leaving room for capabilities.

Implications of the Argument

This is an optimistic thesis because it suggests that Robert Gordon's prediction of the imminent end of modern economic growth may be significantly exaggerated. Gordon describes several headwinds currently facing economic growth but the main findings of the thesis suggest that he is ignoring an important tailwind. If falling knowledge access costs ushered in the age of innovation during the British Industrial Revolution, then the further sharp reduction currently taking place due to declining computing and communication costs is likely to speed up technological innovation in the decades ahead. Moreover, the broadening application of artificial intelligence and machine learning to sectors such as medicine, transportation and manufacturing appear likely to have a significantly positive effect on productivity.

Yet, although Gordon may have overestimated the likelihood of technological stagnation in the coming decades, we must also consider a competing dystopia. Technological change is always a mixed blessing, exposing us to both economic and psychological gains and losses. We cannot take it for granted that accelerating technological innovation and productivity growth will give rise to higher average living standards within a reasonable time frame, nor that the transitional costs to society of adopting new technologies will be comfortably low. We already face challenges related to the current vintage of technological progress in the form of technological unemployment (Brynjolsson & McAfee 2011), the rising concentration of national income (Piketty 2013), negative effects of the use of computers on mental health (Bauman & Rivers 2015), the increased capabilities of terrorists (Bouchard 2015) and the risks that artificial intelligence poses to human safety (Bostrom 2014). If technological progress accelerates in the years and decades ahead, these problems could become more acute. These risks seem large and plausible enough to warrant effort by governments to take measures now to mitigate excessive damage before the underlying problems become larger and more difficult to address.

Thesis Approach and Chapter Outline

This thesis argues that Knowledge Access Institutions facilitated the British Industrial Revolution. The approach taken is to specify the relevant questions in testable form, using theoretical models where necessary, and to build new datasets to help answer them.

As discussed below, there is an existing literature of case studies and prosopography of the organisations that composed the KAI infrastructure, which has produced a significant amount of insight into their role during the British Industrial Revolution (Musson & Robinson 1968, Schofield 1963, Inkster 1991, 1998, Jacob 1997, 2014, Jacob and Stewart 2004, Mokyr 2002, 2005). The aim of this thesis is not to add to this research by producing more case studies, but rather, to provide an alternative type of analysis based on formal economic modelling and statistical identification. The main reason for doing this is to address the main critique made of the existing case study-based literature: that the evidence brought to bear so far is not falsifiable in nature (Crafts 2011, Allen 2011). As such, the thesis aims to move the debate beyond this obstacle.

The approach to statistical identification taken relies on the spatial and temporal relationships between variables *within* Britain during the Industrial Revolution. So far, this approach has arguably been under-utilised in the study of the British Industrial Revolution[8]. As such, it is hoped that the creation of new within-Britain spatial and panel databases on

[8] Although two important recent exceptions to this are Crafts & Wolf (2014) and Kelly, Mokyr & O'Grada (2014)

technological innovation and its potential determinants (along with some datasets related to the onset of modern economic growth in nineteenth century America) is a useful contribution to the study of the British Industrial Revolution and provides a foundation for more work along these lines.

Chapter Outline

Chapter 1 provides a summary of the current debate on the relative importance of British supply-side capabilities and demand-side incentives to the British Industrial Revolution. It focuses mainly on the recent arguments made by Joel Mokyr – in favour of the supply side – and Robert Allen – in favour of the demand side – in their respective books, both published in 2009, and on the analytical joint review of the two books by Nicholas Crafts (2011).

In chapter 2, I make the central argument of the thesis: that Knowledge Access Institutions facilitated technological innovation during the British Industrial Revolution. First, I discuss the key quantitative dimensions of the British Industrial Revolution established by Crafts (2014), to which any explanation for the British Industrial Revolution must relate. Second, I define the concept of KAIs and introduce the data collected for the thesis on the landscape of British KAIs during British Industrial Revolution. Third, I explain how KAIs affected technological innovation through a general equilibrium analysis and then from a microeconomic perspective drawing on findings in management science and network theory. I argue that KAIs raised the productivity and supply of R&D in the British economy and that they can help explain the fundamental quantitative dimensions of the British Industrial Revolution set out by Crafts.

In chapter 3, I present empirical evidence of the effect of KAIs on technological innovation during the British Industrial Revolution. The empirical strategy employed is based on the idea that KAIs would have had a greater impact on innovation in their locale than further away. I construct panel datasets on proxies for technological innovation, and test using econometric methods whether the spatial and temporal patterns of technological innovation during the British Industrial Revolution can be explained by KAIs. These original datasets comprise a panel dataset of all patents registered in England by British patentees prior to 1852, including details of patentee name, residence, occupation, description of patent, industrial sector and a quality index based on a reference index; a spatial dataset of all of the British exhibits at the Great Exhibition of 1851, including details of residence of exhibitor, industry sector and whether each exhibit won a prize at the exhibition or not; and a panel dataset of all US agricultural patents filed prior to 1873. Estimates based on these datasets find consistent evidence of a significant effect of KAIs on technological innovation.

In chapter 4, I argue that KAIs were not fundamentally endogenous to the Industrial Revolution, but rather a product of the European Enlightenment. First, I illustrate in the context of the Romer-Mokyr model of chapter 2 why endogenous innovation is difficult to achieve and why purely endogenous innovation, and hence endogenous KAIs, during the British Industrial Revolution seems implausible. Second, I argue that KAIs were funded by an exogenous 'Enlightenment subsidy', based on the non-profit utilities of KAIs associated with the cultural and ideological preferences of the European Enlightenment. I describe the individual sources of this subsidy by surveying the literatures on the history of eighteenth century science, religion and culture. I provide falsifiable empirical evidence of the Enlightenment subsidy by analysing the spatial links between late seventeenth and early eighteenth century Rational Dissent and the eighteenth-century adoption of KAIs. I exploit exogenous variation in the spatial distribution of Rational Dissent across England due to Charles II's 'Five Mile Act' of 1665, which banned Rational Dissent in certain parts of the country.

In chapter 5, I explore the possible influence of KAIs on the emergence of modern economic growth beyond the British case in the late nineteenth and early twentieth centuries. I present a simple positive cross-country correlation between KAIs and economic growth during this period. Then, I carry out an analysis of the sensitivity of national and US state-level rates of technological innovation to the cost of access to knowledge in the late nineteenth and early twentieth centuries, based on variation in knowledge access costs due to the expansion of national and state-level railway systems. I construct datasets on national patenting rates and railways between 1883 and 1913 and US state-level patents and railways between 1840 and 1890. To distinguish between the knowledge access and market access effects of rail on innovation at the national level, I measure the respective effects of passenger and freight volumes as proxies, and at the US state-level I use patent citation data to investigate the link between rail and patent quality, arguing that patent quality is likely to be affected by knowledge access but not market access. I show that technological innovation was sensitive to knowledge access costs in the late nineteenth and early twentieth centuries and argue that this implies that

KAIs were operating upon an active constraint to modern economic growth in numerous countries during this period.

In chapter 6, I investigate the influence of demand-side incentives as opposed to supply-side capabilities on the emergence of modern economic growth in the case of the late nineteenth century US manufacturing sector. Noting that Bob Allen's argument for the British Industrial Revolution also applies to the late nineteenth century US case, I specify four empirical implications of Allen's argument and test their validity using a county-decade panel dataset based on the nineteenth century US manufacturing censuses between 1870 and 1900. I find support for Allen's argument that technological change during the emergence of modern economic growth was labour saving and that capital deepening was sensitive to the cost of labour relative to capital and subsequently gave rise to an elevated rate of learning by doing. I also find support for the basic claim central to Allen's argument that innovative effort was sensitive to prospective returns. Nevertheless, Allen's demand-side incentives cannot explain the full force of the emergence of modern economic growth in US manufacturing, leaving room for the influence of supply-side capabilities.

The table below summarises the datasets constructed for the thesis. The collection of new data was a major part of the overall project and took a number of years to complete. I have digitised data from archival, library and online sources and geocoded them to produce original spatial datasets. These are the basis for the illustration of the KAI system, the empirical identification of KAIs as a cause of the British Industrial Revolution, and the investigation of related questions.

Table I.1: Summary of Databases Constructed and Used

Datasets constructed by the author	**Source**
British Core Knowledge Access Institutions 1700-1851 panel, by census registration district, hundred & county	Various, see appendix to chapter 3
British 'Core' Knowledge Access Institutions 1851 cross section. Fields: membership, books, lectures, fees, by census registration district	1851 education censuses of England, Wales and Scotland, BPP
British 'Peripheral' Knowledge Access Institutions 1700-1851: Public Libraries. panel by census reg. district & county	Raw data from Robin Alston's Library History Database http://digitalriffs.blogspot.co.uk/2011/08/robin-alstons-library-history-database.html
British 'Peripheral' Knowledge Access Institutions 1700-1851: Masonic Lodges in England. panel by census reg. district & county	Raw data from Lane's Masonic Records 1717-1894 http://www.hrionline.ac.uk/lane/
British 'Peripheral' Knowledge Access Institutions 1700-1851: Booksellers in England. panel by census reg. district & county	Raw data from The British Book Trade Index http://bbti.bodleian.ox.ac.uk/
US Agricultural KAIs. County panel 1730-1870. Fields: membership, meetings, fairs, volumes in library, correspondence with state society.	US Department of Agriculture (1876) *List of Agricultural Societies…*
Great Exhibition 1851 exhibitor and prize winner counts, by British census registration district. Fields: address, sector, prize status.	Royal Commission of the Great Exhibition of 1851 (1852), *Reports by the Juries on the Subjects in the Thirty Classes into Which the Exhibition was Divided (in Four Volumes)*, London. Royal Commission of the Great Exhibition of 1851 (1851), *Official Descriptive and Illustrated Catalogue of the Great Exhibition of the Works of Industry of All Nations 1851*, London.
British patentees 1617-1852 panel , by British census registration district and county. Fields: Name, date of application, address, sector, Woodcroft Reference Index (citation based quality measure), short description.	Woodcroft B (1854) *Titles of Patents of Invention Chronologically Arranged, 1617–1852*. London. (Located in the British Library, London) Woodcroft B (1855) *Reference Index of English Patents of Invention, 1617-1852*. London. (Located in the British Library, London)

English dissenting congregations, 1729 cross section by English hundreds. Fields: (congregation size, denomination of dissent)	*The Evans List*, Dr Williams', located at the Library for Dissenting Studies, Bloomsbury, London
English Unitarian congregations panel 1660-1850	*Alan Ruston's list of Unitarian congregations*
Marriage register mark rates (literacy estimate) various cross sections during nineteenth century by registration district.	*Annual Reports of the Registrar General*, BPP
Population panel by hundred, registration district and county populations, various cross sections	Various censuses, BPP; Wrigley E.A. (2012), *'The Early English Censuses'* Wrigley, E.A (2009) 'Rickman revisited: …'
US patents, panel 1790-1873, counties and states panels. Fields: patentee name, location, date, sector, brief description, citations received (see dataset below)	Raw data from Patent and Trademark Resource Centre Association, 2013, in turn based on the *Subject Matter Index of Patents for Inventions by the United States Patent Office from 1790 to 1873 Inclusive (USPO 1873)*. Sector codes from USPTO database (2013)
US agricultural patents 1790-1873, counties and states panels. Fields: patentee name, location, date, sector, brief description, citations received (see dataset below)	Raw data from Patent and Trademark Resource Centre Association, 2013, in turn based on the *Subject Matter Index of Patents for Inventions by the United States Patent Office from 1790 to 1873 Inclusive (USPO 1873)* Sector codes from USPTO database (2013)
US patent citation counts panel 1790-1873, by county and state.	Raw data from Hall, Jaffe and Trajtenberg (2001) Matched to above databases by patent number.
US manufacturing census variables, county and state level panels 1840-1900 (ten year intervals), Fields: labour stock, capital stock, output, raw materials, wages	Minnesota Population Center. National Historical Geographic Information System: Version 2.0. Minneapolis, MN: University of Minnesota 2011, www.NHGIS.org
US agricultural census variables, county and state level panels 1830-1870 (ten year intervals). Fields: labour stock, capital stock, output, wages	Minnesota Population Center. National Historical Geographic Information System: Version 2.0. Minneapolis, MN: University of Minnesota 2011, www.NHGIS.org
US population census variables, county and state level panels 1830-1870 (ten year intervals). Fields: urban and rural populations	Minnesota Population Center. National Historical Geographic Information System: Version 2.0. Minneapolis, MN: University of Minnesota 2011, www.NHGIS.org
School attendance ratios by census reg. districts and counties, 1851	England and Wales, and Scotland Education Censuses 1851, BPP

Datasets donated by other authors	
Occupational census cross section 1851, by British registration district	Donated by Leigh Shaw Taylor & the Cambridge Population Group
Estimated occupational census cross section 1817, by English registration district	Donated by Leigh Shaw Taylor & the Cambridge Population Group
Market access index by US counties 1870	Donated by Dave Donaldson (Donaldson D & Hornbeck R 2015)
Other datasets used	
International rail panel data, annual 1825-1913. Fields rail length, passenger volume, freight volume	Mitchell B (2007a, 2007b, 2007c)
Annual national patent counts, panel of 21 countries, 1883-1913	World Intellectual Property Organisation
Annual national GDP, population, GDP per capita, various countries and years	Broadberry S & Klein (2011) Maddison A (2013)
2014 US company financial data aggregated by sector on R&D investments and profit rates	Damodaran A website at Stern Business School, NYU http://pages.stern.nyu.edu/~adamodar/

Chapter 1

The Debate: Capabilities versus Incentives

Two books published in 2009 have sharpened the focus of the debate on the causes of the British Industrial Revolution. In *The British Industrial Revolution in Global Perspective*, Robert Allen argues that the Industrial Revolution happened in eighteenth century Britain because it was profitable for it to happen there (Allen 2009). He claims that eighteenth century Britain's high wages and cheap energy, along with a sufficiently large market for capital goods, induced the invention and adoption of the famous labour saving macroinventions of the Industrial Revolution. This in turn put the British economy on a path of rising capital intensity, which was conducive to further technological progress via further rising wages and learning-by-doing (Arrow 1962). Allen thus believes that fortuitous *incentives* facing British inventors and entrepreneurs in the eighteenth century incentivised the acceleration in technological innovation that characterised the Industrial Revolution.

In contrast, in *The Enlightened Economy*, Joel Mokyr argues that eighteenth century Britain experienced the first Industrial Revolution not because of the incentives it faced, but rather because of the *capabilities* that it possessed (Mokyr 2009). Unlike any other nation, Britain was willing and able to supply the technological innovations of the Industrial Revolution. Such capability was critically dependent on the application of a scientific approach to the accumulation of industrial knowledge, a pro-technology ideological climate acting upon both government policy and individual behaviour and the relatively high technical skill level of British engineers and mechanical operatives. Mokyr credits the first two of these capabilities to the eighteenth century European Enlightenment.

In several ways, it seems natural to pit Allen and Mokyr's arguments against one another[9]. Allen argues for incentives, Mokyr capabilities; Allen the demand for technology, Mokyr the supply of technology; Allen economic determinism, Mokyr 'mind over matter'. Nevertheless, as Crafts emphasises in his analytical review of the two books, Allen and Mokyr speak in unison on the most fundamental issue (Crafts 2011). In Crafts' words, a satisfactory

[9] Indeed, both Allen and Mokyr downplay the other's thesis (Mokyr 2009, Allen 2009).

explanation for the British Industrial Revolution must "take technological change seriously" (Crafts 1995) and both Allen and Mokyr put technology at the centre of the story. Both also argue on the basis of extensive empirical study of technological innovation and of the characteristics and incentives of inventors and adopters of technology during the British Industrial Revolution (Mokyr 1990, Allen 2009). Other prominent accounts of the British Industrial Revolution, which emphasise coal (Wrigley 2010), colonialism (Pomeranz 2000) and political institutions (North & Weingast 1989, Acemoglu & Robinson 2012) do not provide a comparably rich explanation for eighteenth and nineteenth century British technological innovation and its characteristics.

Moreover, Allen and Mokyr's explanations for the British Industrial Revolution are not mutually exclusive. One can accept both Allen's argument that factor prices stimulated technological change in eighteenth century Britain and Mokyr's emphasis on the elasticity of supply. Indeed, the most fruitful line of investigation is probably to establish the correct balance of emphasis between the two (Crafts 2011). Was Britain's response to Allen's incentives basically passive, or was it substantively conditional on Mokyr's capabilities? Was necessity the 'mother of invention' in the British Industrial Revolution, or was she instead the 'midwife', helping to deliver the transition to modern economic growth?

Britain's Incentives: Induced Innovation, Resource Availability and Political Institutions

To explain the British Industrial Revolution, Allen reasons in the tradition of John Hicks (1932), who claimed that: "The real reason for the predominance of labour-saving inventions is surely that…a change in the relative prices of the factors of production is itself a spur to innovation and to inventions of a particular kind – directed at economizing the use of a factor which has become relatively expensive" (1932, pp.124-5). Hicks' argument has been employed previously by H.J. Habakkuk (1962) to explain how scarce labour and abundant resources gave rise to US technological pre-eminence in the nineteenth century, and was subsequently formalised by Paul David (1975) and later by Daron Acemoglu (2002). Allen essentially applies David's model to the eighteenth century British case, describing the British Industrial Revolution as the 'prequel' to Habakkuk's America.

Allen has shown that eighteenth century Britain was a comparatively high wage, cheap energy economy and that, dependent on certain assumptions, a selection of the important 'macro-inventions' of the British Industrial Revolution, namely, the spinning jenny, the steam engine and coke smelting, were more profitable to adopt in eighteenth century Britain than elsewhere. He argues that this made them more likely to be invented in Britain too (Allen 2009). Some of Allen's assumptions have been questioned, such as Allen's microeconomic assumptions about the usage of the technologies (see Crafts 2011). But the most basic objection is that high British wages do not necessarily mean that British labour was expensive. To calculate unit labour costs, wages must be compared to productivity. Indeed, Kelly, Mokyr and O'Grada (2014) argue that higher wages in Britain than France during the eighteenth century simply reflected higher productivity levels, which were a function of superior British human capital. Unit labour costs may even have been comparatively low in Britain.

Nevertheless, taking Allen's evidence in favour of expensive labour at face value, Allen has advanced the microeconomic history of some of the major inventions of the Industrial Revolution. However, to ascertain the overall importance of Allen's incentives to the British Industrial Revolution – and to weigh this against the importance of supply side capabilities – one requires an indication of the size of their effect on the overall rate of technological innovation. Did factor prices influence the geography of invention and technological adoption in general in the way that they influenced the birth of the spinning jenny? Furthermore, did differential technology adoption rates across countries, reflected in capital-labour ratios, determine the subsequent rate of micro-inventions? Can this causal chain explain the bulk of productivity growth during the British Industrial Revolution? Indeed, can it also, as Allen claims, explain the patterns of modern economic growth at the global level during the past two centuries? (Allen 2012).

For Allen, the fact that many countries remain without sustained economic growth is due to self-reinforcing patterns of relative factor prices into which they are locked, which discourage technological innovation. Low wage countries are not incentivised to pursue the capital-intensive path that would give rise to a self-sustaining cycle of labour-saving innovation, learning by doing and higher wages and thus further labour saving innovation. Divergent paths of relative factor prices explain the Great Divergence in incomes between rich and the poor countries. Initial lucky breaks and subsequent path dependence have proven to be decisive, while relative capabilities for technological innovation have been incidental.

Allen supports this explanation for the Great Divergence with an empirical study that shows a link between national capital-labour ratios and subsequent labour productivity growth at various cross-sections during the past two hundred years (Allen 2012). He shows that since the British Industrial Revolution, significant labour productivity growth has occurred only in the economies that were already operating at high capital-labour ratios. In contrast, countries with low capital-labour ratios have barely raised labour productivity at all, and the small gains that they have made have been due to small increases in the capital-labour ratio, not by technological innovation. This is a view of long-term economic growth akin to that of Atkinson and Stiglitz's (1969), in which technical change as localised to certain capital-labour ratios. This contrasts with the dominant view of long term economic development based on technical change that is neutral across capital-labour ratios (Hicks 1932, Solow 1956) and hence accessible to all given the right capabilities.

Certainly, this evidence speaks to the important question of the overall impact of factor prices on technological progress and economic growth. However, it is subject to a major omitted variable problem. The economies that have made progress on the high wage, capital-intensive growth path since the British Industrial Revolution may simply be the countries that possessed the necessary capabilities for modern economic growth. Moreover, if those capabilities are difficult to attain but highly persistent once attained then the winners would tend to pull away from the losers over time. Indeed, countries that have moved from the latter to the former group have tended to experience concurrent institutional improvement, such as China, which has experienced both pro-market reforms and an acceleration in economic growth since the late 1970s (Brandt, Ma & Rawski 2013).

To explain Britain's high wages on the eve of the Industrial Revolution, Allen invokes the effects of Smithian productivity growth due to its high degree of engagement in international trade and high urbanisation rates. Kenneth Pomeranz (2000) attributes the British Industrial Revolution more directly to trade, particularly Britain's trading advantages owed to the British empire. For Pomeranz, Britain's colonies – alongside her coal deposits – were crucial because they provided access to the raw materials that allowed the British Industrial Revolution to progress without encountering resource constraints. Britain's access to cheap energy, even as its energy usage increased manifold, and colonially sourced raw cotton enabled a development path centred on the global expansion of the cotton textiles industry, eventually powered by steam. Although Pomeranz highlights manufacturing inputs in general, he is greatly influenced by Wrigley's articulation of the fundamental energy constraints to historical economic development (Wrigley 2010). Wrigley views the British Industrial Revolution as the transition from an 'organic economy', which is limited in its energy usage by land availability, to a 'mineral-based economy', which can circumvent this constraint through the exploitation of fossil fuels. Like Allen, both essentially attribute the British Industrial Revolution to incentives in the form of factor prices, though unlike Allen they fail to identify an explicit mechanism for *sustained* innovation.

The final class of prominent incentive-based arguments focuses on political institutions. Douglas North and Barry Weingast (1989) have claimed that the political settlement achieved in England following the Glorious Revolution of 1688-89 strengthened parliamentary oversight of the king, thereby reducing the risk of state tyranny to investment and innovation. Daron Acemoglu & James Robinson (2006, 2012) see the development implications of the Glorious Revolution within a framework for interpreting world history that distinguishes between 'extractive' and 'inclusive' institutions. In extractive institutions, the ruling elite has a high degree of control over the economy and seeks only to maximize its own rents. This tends to retard economic development. In contrast, inclusive institutions provide broader access to the political system, which results in policies and laws that are consistent with value creation across the economy. Steven Pincus and Robinson (2014) see the important aspect of the Glorious Revolution for development as the rebalancing of policymaking rights away from the king to parliament, which represented the interests of the emerging commercial class through the Whig party. This meant that Britain's political institutions switched from extractive to inclusive institutions. North, Wallis and Weingast (2006) construct a framework similar to Acemoglu and Robinson based on the concept of limited-access and open-access social orders, with similar differential effects on growth. The shortcoming of these arguments, although persuasive as essential pre-conditions for growth, is that they take for granted the elasticity of the supply of technological innovation with respect to incentives.

Britain's Capabilities: Nuanced Notions of Human Capital

By emphasising the incentives for technological innovation, the above explanations for the British Industrial Revolution give no credit to the skills of eighteenth century British inventors and entrepreneurs for the supply of innovation. Certainly, this assumption is corroborated by conventional measurements of human capital for eighteenth century Britain – such as school enrolment and literacy – which cast eighteenth century Britain as unexceptional relative to peers (Mitch 1999, Lindert 2004). Moreover, nor did human capital based on these measures improve as the British Industrial Revolution progressed. Across Britain, schooling rates and industrialisation were inversely correlated across regions, partly because of the demand for child labour in the textiles industry. Literacy rates fell in the industrialising areas of Britain during the Industrial Revolution (Stephens 1987).

Recently, however, research on eighteenth century Britain's capabilities has begun to shed light on more nuanced concepts and measures. There is a growing focus, as advocated by Crafts (1996), on the role of human capital in raising the rate of TFP directly, as opposed to augmenting the effective labour supply, as envisaged in the traditional view of human capital formalised in the augmented Solow growth model. This shift mirrors recent research by education economists, such as Hanushek and Woesmann (2015), who stress the effect of human capital levels on economic growth via technology adoption rates (Nelson and Phelps 1966) as opposed to the effect of human capital growth rates, operating through gains in effective labour units.

This agenda has been spearheaded by Joel Mokyr (2002, 2005, 2009, Meisenzhal & Mokyr 2012, Kelly, Mokyr & O'Grada 2014), who de-emphasises average workforce levels of human capital in favour of a focus on human capital levels at the upper end of the skill distribution. Moreover, Mokyr also argues that skills are poorly captured by literacy and school enrolment rates and that strong and rising stocks of the relevant components of human capital are reconcilable with mediocre and falling literacy and school enrolment rates. Indeed, Mokyr's observation that the ingenuity of Britain's innovators during the Industrial Revolution was a substitute for the skill of ordinary workers suggests a mechanism by which a rise in upper tail human capital could even reduce human capital levels lower in the distribution.

Mokyr argues that three capabilities were jointly responsible for the British Industrial Revolution. The first was the capability to apply a scientific approach to industrial R&D, the product of what Mokyr refers to as the 'Industrial Enlightenment' (Mokyr 2002, 2005). The Industrial Enlightenment was a Western Europe-wide cultural phenomenon rooted in the transcontinental private order institution of the 'Republic of Letters' established during the Scientific Revolution in the three centuries prior to the British Industrial Revolution (David 2014, Mokyr 2016). The Knowledge Access Institutions of eighteenth and early nineteenth century Britain represented an eventual industrial flowering from these roots. Mokyr's argument is influenced by studies of the role of scientific institutions, method, knowledge and culture in the Industrial Revolution by A.E. Musson and Eric Robinson (1968), Robert Schofield (1963), Ian Inkster (1991, 1998), Margaret Jacob (1997, 2014) and Margaret Jacob and Larry Stewart (2004). However, an important difference between Mokyr's Industrial Enlightenment and Jacob's important and otherwise closely related concept of eighteenth century 'scientific culture' is the question of British exceptionalism. For Mokyr, the Industrial Enlightenment did not differentiate British capabilities from those of other Western European countries but rather differentiated Western Europe from the rest of the world, while Jacob sees Britain as playing a leadership role within European scientific culture owing to the empirical, Newtonian bias in eighteenth century British science – which provided a suitable model and impetus for industrial R&D – compared to the theoretical, Cartesian dominance on the continent until late in the century (Jacob 2014).

An important critique of this literature is that relying as it does on case studies, it lacks a falsifiable evidence base (Crafts 2011, Allen 2011). Indeed, McCloskey (2010) questions the possibility of providing any falsifiable evidence whatsoever for cultural foundations of modern economic growth. Other authors reject a major role for science in the British Industrial Revolution (the classic arguments are Hall (1974), Mckendrik (1973), Gillespie (1980), Mathias (1979), recent contributions are O'Grada 2014, Khan 2015), pointing to the absence of an influence of scientific knowledge on textile industry innovation and the low formal education levels of some inventors. But this view fails to acknowledge the difficulty of disentangling scientific and technological knowledge in the eighteenth century prior to the professionalization of science. Indeed, although there were men of pure science in eighteenth century Britain, it may be anachronistic to think of science and technology as meaningfully separate areas of enquiry during this era, given the still immature state of scientific knowledge, particularly the understanding of underlying mechanisms behind empirical regularities, the pervasive Baconian ideology of the pursuit of science for the practical "relief of man's estate" and the limited role of pure scientific institutions such as universities, which remained unreformed and sparse until the introduction of modern research universities, government R&D agencies and corporate R&D departments in the late nineteenth and twentieth centuries. Yet, the scientific age was underway. Above all, the case against the role of science in the British Industrial Revolution focuses too much on the contribution of scientific knowledge and not enough on the impact of scientific culture on industrial R&D: the emulation of the scientific method and the basic scientific belief in the predictability of nature and the possibility of progress in understanding, which made R&D seem like a worthwhile activity. In this spirit, Mokyr (2002, 2005, 2009) and Jacob (1997, 2014) emphasise the links between the Scientific Revolution and the Industrial Revolution in terms of scientific ideology, method, norms and culture as distinct from achievements within scientific knowledge itself.

The second capability was the readiness of the eighteenth and nineteenth century British parliament to change laws in favour of innovators and the users of new technology as the economy evolved (Mokyr 2009). Mokyr argues that the eighteenth and early nineteenth century British parliament was a flexible 'meta institution', which, although probably unimpressive by modern standards owing to limited access and high levels of corruption, proved to represent the allies of technological change well enough to weaken opposition. This gave Britain an advantage because the enemies of technological change were more powerful in other countries. In terms of empirical evidence, Dan Bogart and Gary Richardson (2011) have shown that during the eighteenth century the British parliament was highly responsive to local demands to re-organise property rights for economic development. For Mokyr, political institutions are ultimately determined by ideology, and the stance of Britain's parliament in the eighteenth century was shaped by the European Enlightenment. This view of political institutions contrasts with the view of Acemoglu and Robinson (2012), who see institutions and cultural and ideological forces as largely competing explanations for economic development. They argue that institutional change tends to be stimulated by exogenous shocks at critical junctures.

The third capability was Britain's superior level of human capital compared to its contemporaries, which enabled much higher adoption rates of new technology and techniques. There were two dimensions to this. First the productivity of the British workforce in general was relatively high due to a British advantage in nutrition. Kelly, Mokyr and O'Grada (2014, hereafter KMO) provide evidence that British nutritional inputs and outcomes, such as height, were superior to those in France, and cite biological research that shows a link between nutrition and both physical strength and cognitive development. They argue that good British nutrition was due in part to the effect of the English Poor Laws, which was a unique institution in pre-modern Europe. Second British mechanics and artisans, representing the top 10% or so of the skill distribution of the workforce, were better skilled than those in other economies. KMO stress that once technology is invented it requires competent individuals to build, use, debug and tweak it to generate the bulk of the productivity gains. They cite contemporary accounts that noted the superiority of Britain's mechanics, and net positive migration rates of British mechanics to the continent.

Why were British mechanics highly skilled? Meisenzahl and Mokyr (2012) construct a database of 759 such individuals, showing that most were trained via apprenticeship. KMO argue that Britain's system of apprenticeship was more efficacious in skill acquisition than the apprenticeship systems on the continent. The basic case for this is that, as Chris Minns and Patrick Wallis (2012) and Tim Leunig, Minns and Wallis (2011) show, the British system was particularly flexible and reliant upon informal agreements compared with the rigid guild-based continental system. Ogilvie (2014) argues that guilds exercised a strong interest in maintaining the technological status quo and were poor in general at promoting skill acquisition. As such, the British system of apprenticeship was better at adapting skills to new technology within existing industries and accommodating shifts in labour demand towards these industries as they expanded (Humphries 2003) than those on the continent. In Mokyr's framework, these three capabilities together determined Britain's leadership. When Western Europe and North America attained these capabilities in the nineteenth century, in part stimulated by Britain's example, they followed in Britain's footsteps.

Contribution to the Debate

The research in this thesis is in the spirit of Mokyr's focus on Britain's eighteenth and early nineteenth century capabilities to innovate. Its main contribution is to gather evidence on one of the key capabilities – the capability to access to knowledge cheaply – and test its impact on innovation. Nevertheless, it recognises that the respective arguments of Mokyr and Allen are fundamentally complementary. Both "take technological change seriously" and see the main task of explaining the British Industrial Revolution as ascertaining the proximate mechanism by which inventors and entrepreneurs became more engaged and/or successful in generating technological change. Mokyr argues in favour of supply factors, while Allen argues in favour of demand factors. As such, the thesis seeks to help establish the correct balance of emphasis between British innovators' capabilities and incentives during the British Industrial Revolution.

Chapter 2

Knowledge Access Institutions and the British Industrial Revolution

The British Industrial Revolution marked an important turning point for living standards. We are much richer than our forefathers because we know more than they did, and the knowledge that counts is embodied in the technology – the machines, materials and medicines that make us more productive, healthy and comfortable – at our disposal. Before the British Industrial Revolution, the accumulation of this technology was everywhere slow and sporadic, but since has been rapid and self-sustaining. Why did the flood gates open in Britain in the eighteenth and early nineteenth centuries, eventually raising the standard of living to levels that our forefathers would have found unimaginable?

Nicholas Crafts emphasises two important clues revealed by the measurement of British economic growth during course of the British Industrial Revolution (Crafts 1995, 1996). First, late-eighteenth and early-nineteenth century Britain was indeed the locus of the transition to rapid, sustained, technology-led economic growth, but the transition was gradual. The gate crept open, it did not burst open. Second, although the rate of economic growth achieved at the apex of the British Industrial Revolution was high relative to anything that had been experienced beforehand, it was moderate compared with the rate of growth achieved at the world technological frontier in the twentieth century. In Crafts' words, the British economy forged by the Industrial Revolution was "neither an eighteenth nor a twentieth century economy. Of course not, it was a nineteenth century economy[10]."

Given these facts, this chapter argues that the blossoming of the world's first infrastructure for research and development (R&D) in eighteenth and nineteenth century Britain has an important role to play in the explanation of the British Industrial Revolution. This infrastructure comprised a system of 'Knowledge Access Institutions', or 'KAIs' – learned societies, mechanics institutes, masonic lodges and public libraries, among other organisations – which, over the course of the eighteenth and early nineteenth centuries, steadily reduced the cost of access to useful knowledge for the natural philosophers, inventors and technological

[10] Crafts' Ellen McArthur Lectures 2009, *NFR Crafts, "From the 18th to the 21st Century: a Perspective on 250 Years of Economic Growth"* at Cambridge University (November 2009). Podcast available at http://www.econsoc.hist.cam.ac.uk/podcast-crafts.html

entrepreneurs engaged in the process of technological innovation. In so doing, KAIs gradually raised the productivity of R&D in the British economy, which also raised the equilibrium supply of R&D effort. These two effects lay behind the gradual acceleration in economic growth that characterised the British Industrial Revolution.

How did KAIs reduce the cost of access to knowledge? There were two main mechanisms. First, they promoted the application of the scientific method, the norms of science and even a little bit of scientific knowledge itself to the R&D process in the British economy (Musson & Robinson 1968, Jacob 2014). This resulted in the acceleration of the growth of the knowledge base upon which society could collectively draw to invent new technology (Mokyr 2002). Second, as a networked system spanning Britain and connected to similar scientific institutions abroad, KAIs reduced the cost to inventors and technological entrepreneurs of searching the scientific and technological community for knowledge.[11] Furthermore, by greater connecting the scientific and technological community, the KAI network raised the level of social capital within the overall innovation process, aiding the commercialisation of new ideas[12].

The famous Lunar Society in Birmingham facilitated the transmission of knowledge and cemented the personal relationships that enabled James Watt to commercialise his ideas for the improved efficiency of steam engines (Schofield 1963). What has not been fully appreciated, however, is that as the British Industrial Revolution progressed, each successive generation of inventors following in Watt's footsteps operated within a richer institutional infrastructure for innovation, providing cheaper access to specialised knowledge and contacts. This raised the productivity of innovators and, in turn, greater encouraged their efforts.

At the same time, however, Britain's eighteenth and nineteenth century innovation system based on KAIs was quite basic relative to those established in advanced economies during the twentieth century. The twentieth century institutions of large-scale corporate R&D, research universities and government research bodies[13] enabled a greater division of labour in the search for knowledge, a wider set of solutions to profit-appropriation problems and greater

[11] See Jackson (2010) for a textbook treatment of the effects of networks on economic activity, including communication costs and the diffusion of information.
[12] See, for example, Dasgupta (2005) for an introduction to the economics of social capital.
[13] See Nelson (1993) for an overview of the components of the 'national innovation system'.

capacity to finance R&D than eighteenth and nineteenth century KAIs. As a result, the technological frontier advanced faster during the twentieth century than during the British Industrial Revolution. Thus, while Britain's KAIs can help to explain the origin of modern economic growth, their shortcomings can also help to explain why modern economic growth took a long time to accelerate.

The aims of this chapter are twofold. First, I define and quantify Britain's KAI infrastructure during the British Industrial Revolution. After presenting a taxonomy of KAIs, I present data on the quantitative dimensions of the growth of KAIs in Britain between 1700 and 1850. The picture that emerges is of a major nationwide phenomenon and a plausible determinant of the economy's overall rate of technological innovation.

Second, I explain how Britain's KAIs affected technological innovation during the British Industrial Revolution, illustrating the economic effects of KAIs from both a general equilibrium and microeconomic perspective. I present a hybrid general equilibrium model of Paul Romer and Joel Mokyr's views of the impact of knowledge on economic growth, which captures the overall effect of KAIs on the British eighteenth and nineteenth century economy. Then, I examine the day to day activities of KAIs in the light of modern management science and network theory. This approach also enables a rough comparison of KAIs with twentieth century innovation institutions.

The Clues in the Numbers

The macroeconomic dimensions of the British Industrial Revolution, as established by Nicholas Crafts provide clues about its causes.[14] Any explanation for the British Industrial Revolution must explain not only why the rate of technological innovation was faster thereafter than before, but also Crafts' quantitative description of the rate of technological change during the transition, which contains two observations (Crafts 1995, 1996).

[14] See Crafts (2014) for his most recent estimates.

Table 2.1: Crafts' estimates of British GDP growth and its contributions during the Industrial Revolution

Year	Capital cont.	Labour cont.	Land cont.	TFP Growth	Real GDP Growth
1700-1760*				0.2	0.7
1760-1800	0.35*1.0=0.35	0.5*0.8=0.40	0.15*0.5=0.08	0.4	1.2
1800-1830	0.35*1.7=0.60	0.5*1.4=0.70	0.15*0.1=0.02	0.4	1.7
1830-1860	0.35*2.5=0.88	0.5*1.4=0.7	0.15*0.1=0.02	0.7	2.3

Source: Crafts (2014) except *data for 1700-1760 from Crafts (1985: 45)

Table 2.1 illustrates Crafts' most recent estimates of British economic growth and its factor contributions for consecutive periods between 1700 and 1860 (Crafts 2014). The real GDP growth figures reveal a gradual acceleration, as growth initially increased from an average of 0.7% per annum on the eve of the Industrial Revolution (between 1700 and 1760) to 1.2% in its early decades (1760-1800). It then accelerated further to 1.7% per annum between 1800 and 1830 and 2.3% per annum between 1830 and 1860. How much did technological change, the hallmark of modern economic growth, contribute to this acceleration? Economists often approximate technological innovation's contribution to economic growth by Total Factor Productivity (TFP) growth. During the British Industrial Revolution, the impact of TFP growth increased gradually from 0.2% per year during 1700 to 1760 to 0.4% per year between 1760 and 1830 and 0.7% per year between 1830 and 1860. However, TFP can be quite a crude approximation of the contribution of technological change. On the one hand, TFP growth can overstate the rate of technological progress because it can be affected by economies of scale or changes in institutions or industrial organisation that affect workers' incentives. However, as the acceleration in TFP growth recorded during the British Industrial Revolution was mostly restricted to the sectors of the economy that were revolutionised by major technological innovations, it seems likely to have been due primarily to technological change (Crafts 1985).

On the other hand, TFP growth can also understate the rate of technological progress if the rate of accumulation of capital is increased by the introduction of new technology. Specifically, this will be the case if technological change has a labour-saving bias and the elasticity of substitution between capital and labour is less than one[15], both of which conditions appear to have been satisfied during the British Industrial Revolution (Allen 2009b). Intuitively, capital accumulation is ultimately endogenous to technological change because in the long run the marginal return to the accumulation of existing technology tends to zero. This point is consistent with the strong positive relationship observed across countries between TFP levels and capital stocks (Clark 2007). In any case, the contribution of capital accumulation to economic growth also increased only gradually during the British Industrial Revolution, from 0.35% during 1760-1800 to 0.6% during 1800-1830 and 0.88% during 1830-1860. The engine of technological change warmed up only slowly during the British Industrial Revolution.

Crafts' second observation is that the peak rates of GDP and TFP growth during the British Industrial Revolution were moderate compared to the rates achieved at the world economic frontier in the twentieth century. Crafts' estimate of British TFP growth of 0.7% per annum between 1830 and 1860, the apex of the British Industrial Revolution, is less than half the 1.7% per annum rate of TFP growth achieved by the United States, the twentieth century's frontier economy, between 1900 and 2000 (Shackleton 2013). Eighteenth century Britain witnessed the birth of modern economic growth, but adolescence was a long process and maturity was not reached for nearly two centuries.

These clues tell us that whatever caused the acceleration in the rate of technological change in eighteenth and nineteenth century Britain had only a moderate influence at the start, and gradually became more influential over time. This means that any factor that would have affected technological innovation suddenly or, conversely, consistently during the eighteenth, nineteenth and twentieth centuries cannot easily explain the British Industrial Revolution. For example, North & Weingast (1989) and Acemoglu & Robinson (2012) argue that the Glorious Revolution of 1688 was decisive for the British Industrial Revolution because it raised the quality of Britain's political institutions as they pertained to the incentives to innovate and invest. But if this event was decisive, one would expect it to have had quite a sudden effect on technological progress, which is inconsistent with the macroeconomic record. Conversely, North & Thomas 1973 and Bottomley (2015) have argued that Britain's patent system was an important causal factor of the British Industrial Revolution. It may have been a necessary

[15] Intuitively, if the adoption of new technological innovations involved an increase in capital per worker and if the marginal product of capital did not fall too much as capital per worker increased, then TFP growth could miss some of technology's contribution to growth.

condition, but by itself it cannot have governed the gradually rising intensity of the British Industrial Revolution, as the patent system underwent no major reform, nor were costs substantially reduced, from its inception in 1623 until 1852 (Nuvolari and Macleod 2010).

Crafts' second observation suggests that the conditions for technological innovation during the British Industrial Revolution were probably markedly inferior to those experienced during the twentieth century. Nevertheless, it seems plausible that an initial improvement during the eighteenth and early nineteenth centuries in the conditions that eventually produced the high economic growth rates of the twentieth century may have facilitated the British Industrial Revolution. The search for an explanation for the British Industrial Revolution should be informed by our understanding of the forces behind twentieth century economic growth[16].

'Knowledge Access Institutions': Definition and Quantification

One of the major cultural features of eighteenth century Britain was the rise of voluntary associational societies. This had a profound bearing on social and commercial interaction. Voluntary societies increased the number of personal contacts held by the average individual. In the language of network theory, the quantity of these contacts is referred to as the average *degree* of the social network. Moreover, voluntary societies also increased the extent to which cliques of individuals were connected to other cliques through individuals with a foot in each camp – or in network theory terms, the *connectivity* of the social network (Jackson 2010). These two changes in Britain's social network structure facilitated the diffusion of and search for information and raised the level of social capital.[17]

As Roy Porter has illustrated, the phenomenon of voluntary associational societies had a transformative impact on Britain's culture, politics and economy (Porter 2000). Peter Clark's survey of the history of British voluntary associational societies gives one an idea of the scale and diversity of the phenomenon (Clark 2000). Clark estimated the national number of newly established societies per decade as 100 in 1700, 200 in 1750, 400 in the 1760s, 700 in the 1780s

[16] Crafts (1995) explores the British Industrial Revolution using the lessons of modern growth theory. But likeminded research is quite scarce.
[17] See Dasgupta (2005) for an introduction to the social capital literature.

and over 1,000 in the 1790s. This rate of growth overwhelmed that of the population. Among two thousand or so London clubs and societies said to have met by the 1760s were elite arts clubs such as Samuel Johnson's Literary Club and the Dilettanti Society, political societies such as the Whig's Kit-Kat Club and the Tory's White's, the scientific Royal Society, the technological Society for the Encouragement of the Arts and Manufactures, and the historical Society of Antiquaries (Porter 2000). The range was perhaps even more impressive outside of London given much lower population densities. As Porter points out, it did not require a first or even second-tier city to support diversity. For example, Maidstone in Kent had the Maidstone Society for Useful Knowledge (of which Benjamin Franklin and the agriculturalist Arthur Young were corresponding members) alongside "a humane society, assorted drinking and dining clubs, an agricultural society, concert and music societies, 'trapball' and card societies, a book society, a cricket club, party-political clubs, a bachelors' club, freemen societies, benefit clubs, a masonic lodge and, by the mid-1790s, a radical Corresponding Society and an opposing Loyalist association" (Porter 2000).

But which of these organisations had a meaningful impact on the process of R&D, either as an individual institution or as part of a network? At the very least, they must all have facilitated communication *per se*. On the other hand, only a vanishingly small proportion would likely have contributed meaningfully and systematically to the discovery and dissemination of knowledge relevant to technological innovation. One faces, therefore, the difficult task of drawing a line. Which organisations were KAIs and which were not?

An optimist might respond to this challenge along the same lines as US Supreme Court Justice Potter Stewart, who when required in court in 1964 to provide a definition of pornographic material responded: "I know it when I see it". Such an approach might not be too far off the mark. The organisations whose *raison d'être* was to produce and disseminate scientific and technological knowledge documented their aims and activities, leaving behind detailed records. These organisations include major elite scientific institutions such as the Royal Society, the Royal Institution and the Royal Society of Edinburgh, provincial 'middle class' scientific societies, such as the Manchester Literary and Philosophical Society, 'lower class' scientific societies, such as Mechanics Institutes, professional societies such as the Royal Society of Physicians and the Geological Society, and agricultural societies. Many such organisations may have proven ephemeral and have left no record of their existence, but by the same token these individual organisations are unlikely to have been the ones that made a particularly large impact. I refer to this group of societies as *Core KAIs*.

A second class of KAIs, which I refer to as *Peripheral KAIs*, likely influenced the productivity and supply of R&D indirectly by reducing the cost of access to knowledge more generally. They were not disproportionately concerned with science or technology, but provided large scale access to literature and underpinned large social networks. Three such groups of organisations stand out in this respect owing to their scale: public libraries, booksellers and masonic lodges. Moreover, since each operated to some degree as part of a network, their aggregate impact on knowledge access costs was likely non-linear in scale and large relative to organisations that were not as well connected, such as private libraries or independent social clubs. Hence, it seems reasonable to draw the line for peripheral KAIs at this point.

Based on this taxonomy, I present below a brief description of each of the parts of the British KAI system, along with their quantitative dimensions from the start of the eighteenth century to the mid-nineteenth century. I show that while the KAI infrastructure was sparse in 1700, by 1850 it had a major institutional presence, transforming the environment for innovative activity during the interim. I discuss the activities and origins of KAIs only briefly in this section, exploring these aspects later in the chapter and in chapter 4.

Core KAIs

National Scientific Institutions: This group of elite KAIs acted as central nodes of the core KAI network and as propagators of scientific culture and knowledge. The Royal Society, founded in 1660, was Britain's first core KAI and although its research focus on applied science waned somewhat during the late eighteenth century in favour of abstract theory (Miller 1999), it nevertheless played a major role in the British Industrial Revolution via four channels. It provided the ideological and operational blueprint for core KAIs, acted as the central node in the communication network of British core KAIs (through shared membership, correspondence and publication), acted as arbiter of scientific legitimacy within the core KAI system and incentivised scientific and industrial research in the form of its prestigious *FRS* fellowships.

The ideology of the Royal Society must be understood first in the context of the society's origin as a post within the pan-European institution of the 'Republic of Letters', a correspondence community of natural philosophers embodying the Scientific Revolution (Mokyr 2016). However, while many of the natural philosophers across the Republic of Letters were supported by state patronage[18], the Royal Society was operationally and financially independent of the British state, the purpose of its Royal Charter in 1662 being only to elevate its status within the European context. Such political autonomy remained the exception rather than the rule among the scientific institutions that emerged across Europe in the seventeenth and eighteenth centuries. For example, the premier French institution, the *Académie des Sciences,* founded in Paris seven years after the Royal Society, was funded and operated by the state.

Second, the natural philosophers who founded the Royal Society were heavily influenced both ideologically and practically by the early seventeenth century writings of Francis Bacon. In his *New Atlantis* of 1627, Bacon advocated the establishment of a 'House of Salomon', a research institution to scientifically investigate the laws of nature for the "relief of man's estate". The society's founders – who had been meeting informally in London and Oxford since the 1640s to discuss science in the spirit of Baconian philosophy – implemented this vision by establishing an elected membership, lectures and a scientific journal and purchasing scientific equipment with which to carry out scientific experiments. Above all, they followed and promoted Bacon's articulation of the scientific method and promoted a scientific culture.

The Society for the Encouragement of Arts and Manufactures[19] was founded in 1754 to focus on the technological application of science, in principle creating a division of labour between itself and the Royal Society (Chambers 2007). Indeed, there was a large overlap between the membership of the two institutions, 60 percent of the society's original members being Fellows of the Royal Society. The Society for the Encouragement… awarded prizes (called 'premiums') for technological innovations funded by its membership subscriptions, and disseminated these innovations through its journal. In 1799, the Royal Institution was added to the London scene. It sought to reach beyond the elite scientific community through public

[18] Except for three short-lived failed attempts to establish scientific academies in Italy during the seventeenth century.
[19] Later renamed the Royal Society of Arts (RSA).

lectures, such as the celebrated chemistry lectures of Humphry Davy held during the first decade of the new century. Finally, in 1831 the British Association for the Advancement of Science (BA) was founded to promote science outside of the capital and facilitate the national interaction of scientists. The main activity of the BA was its annual gathering at which scientists gathered to present scientific papers, held first in York in 1831 and then in different towns and cities each successive year. These institutions, along with the Royal Society of Edinburgh, a Scottish version of the Royal Society founded in 1783, acted as the backbone of the British establishment scientific community during the Industrial Revolution.

Provincial Literary and Philosophical, and other Scientific, Societies: One the one hand, provincial scientific societies, which began to emerge during the final quarter of the eighteenth century, extended the network of the national elite institutions. They were founded and populated by local elites, who were often members of the metropolitan elite societies, and corresponded with and subscribed to journals of the metropolitan elite societies. Through these connections they inherited the Baconian ideology and institutional format of the Royal Society. However, at the same time, the provincial scene exhibited a degree of ambivalence towards the London scientific community, just as London often projected indifference to the provinces. Some of the most significant provincial societies, such as the Manchester Literary and Philosophical Society (1781) and the Derby Philosophical Society (1783), were instigated by members of the Lunar Society**,** an informal society founded in Birmingham in 1765 by a group of 'super-star' natural philosophers, inventors and entrepreneurs, who at times operated quite independently of the metropolitan elite. The members of both the Lunar Society and many of the subsequently formed provincial societies were disproportionately of anti-establishment religious and political orientation,[20] such as non-conformists and Whigs, if not outright reformists. By the 1820s, such core KAIs existed in most major cities, including Sheffield, Bristol, Liverpool, Bath, Newcastle and Leeds.

Professional Societies: By the second quarter of the nineteenth century, the market for science, and the body of scientific knowledge itself, had expanded to a size that could support specialised KAIs. Previous attempts to specialise, such as various short-lived societies focused on chemistry founded at the turn of the century, had failed[21] but by the 1830s, societies such as

[20] as I discuss at length in chapter 4.
[21] Although the Spitalfields Mathematical Society of 1717 was a notable outlier.

the Royal Geographical Society (1830), the Edinburgh Geological Society (1834), the Royal Institute of British Architects and the Royal Artillery Institution (1838) were successfully established and sustained. On the one hand, specialisation meant that progress in the accumulation of propositional knowledge might be quicker. However, on the other hand, occupationally delineated KAIs had far fewer opportunities to combine and transfer knowledge across different areas of study and application, and may have produced an environment in which – similar to that of medieval guilds (Ogilvie 2014) – members were incentivised to oppose technological change to preserve mutual rents.

Mechanics Institutes: The mechanics institute movement began in 1823 with the establishment of the London Mechanics Institute and was national in scope, there being around 800 mechanics institutes around the country by mid-century (BPP 1852). They were inspired by the physician George Birkbeck's ideological campaign to expand the Baconian scientific franchise beyond the elites to the lower classes (Kelly 1992). Mechanics institutes were run by members of the local elite societies (see Inkster 1997 for case studies of Liverpool and Sheffield), who gave lectures in science, but the inter-class social connections that were formed – for example between gentleman scientists and mechanics – may have been more important than the lectures themselves. Mechanics institutes also provided classes on reading and writing to the lower classes aiding their capacity to absorb new knowledge. They were a precursor to British further education, which emerged in the late nineteenth century. Indeed, they served as its physical infrastructure in its early stages (Walker 2012).

Figure 2.1 presents a time series of core KAIs between 1700 and 1851, which has been constructed for this thesis based on the primary and secondary sources listed in the appendix to this chapter. The core KAI infrastructure grew enormously during this period. On the eve of the British Industrial Revolution, around the mid-eighteenth century, there were less than a handful of core KAIs in existence – the Royal Society, the recently founded Society for the Encouragement of the Arts in London and the informal Lunar Society in Birmingham. Together they had only a couple of thousand members. By 1851, however, around the apex of the British Industrial Revolution, there were around 1,000 core KAIs with approximately 160,000 members in total, representing around 1% of the adult population.[22] Moreover, by 1851, the

[22] I have calculated this aggregate membership figure using a comprehensive survey of learned societies and mechanics institutes in the 1851 Census of Education for Great Britain.

Figure 2.1: Core KAIs in Great Britain, 1700-1851

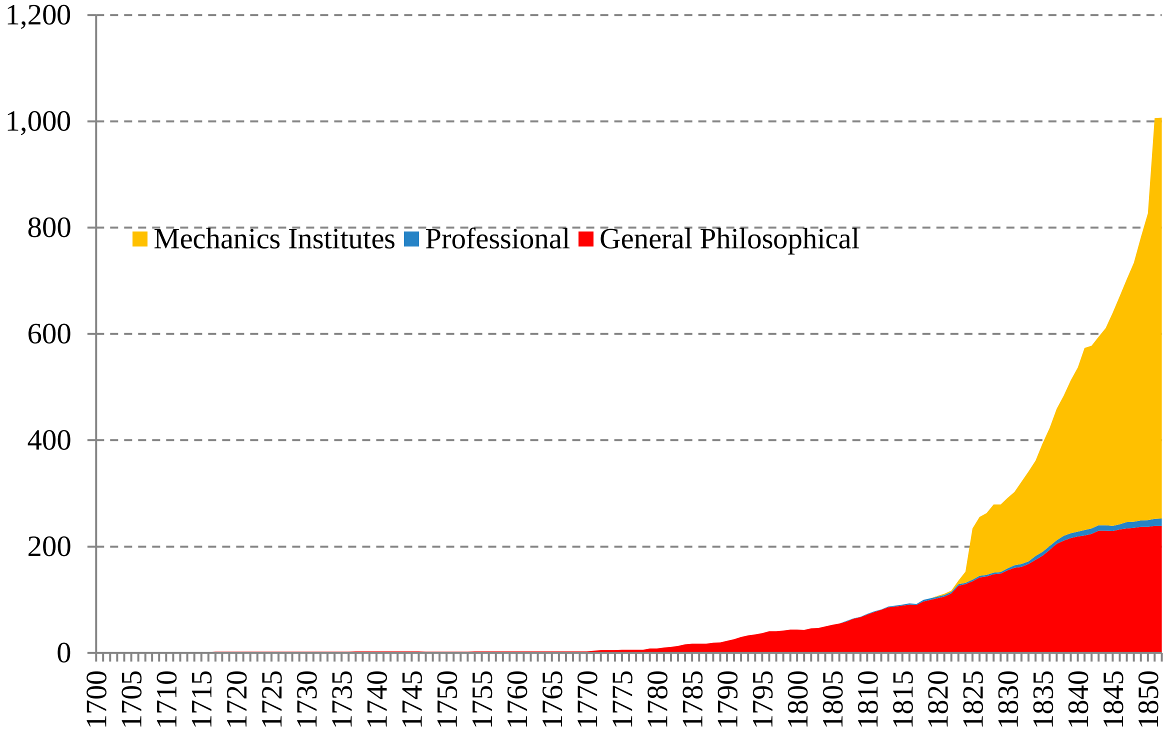
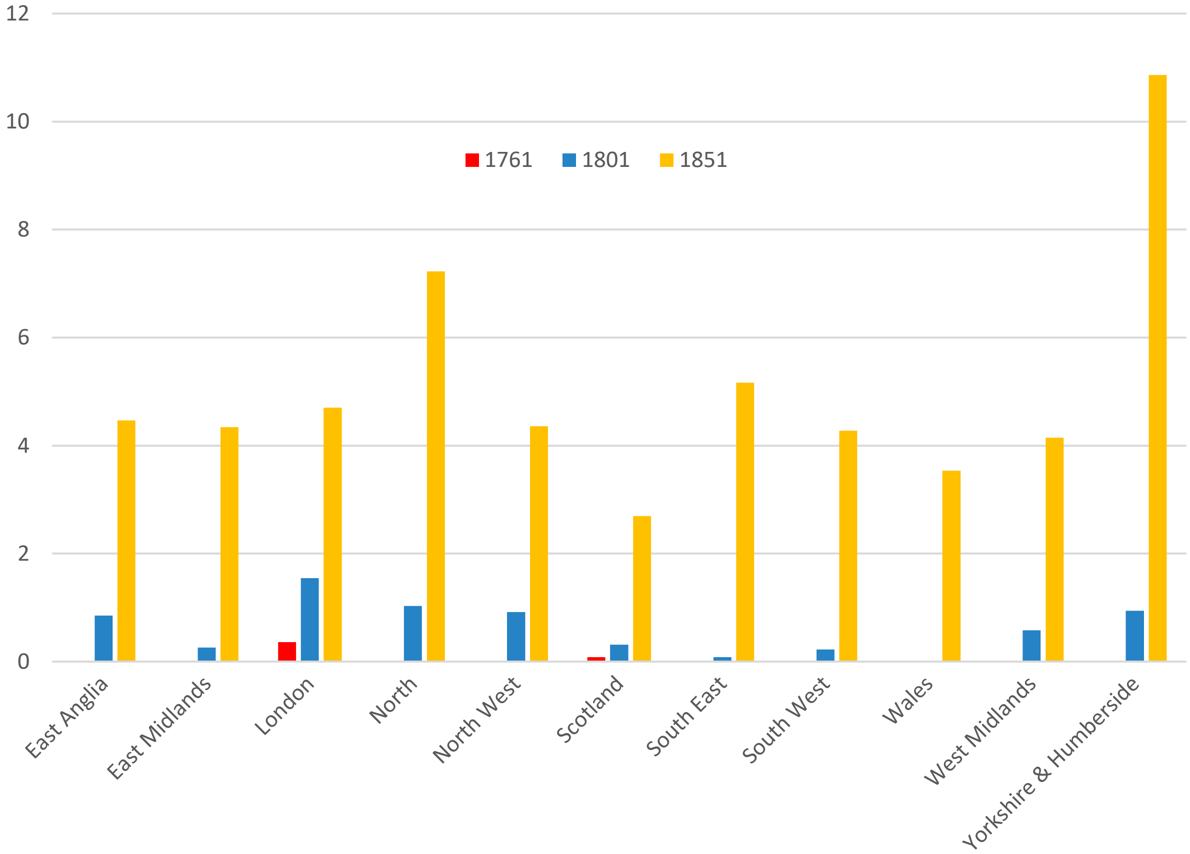


Figure 2.2: Core KAIs per 100,000 Capita by British region, 176, 1801 & 1851



geographical coverage of core KAIs was broad. Figure 2.2 displays regional counts of core KAIs per 100,000 capita for 1761, 1801 and 1851. Although in 1761 the infrastructure was highly localised, and in 1801 still patchy, by 1851 significant ratios of core KAI per capita had been established in each British region.

Figure 2.3: Core KAIs: Histogram of lectures per year across KAIs, 1851 (not including KAIs with more than 1 lecture per week)

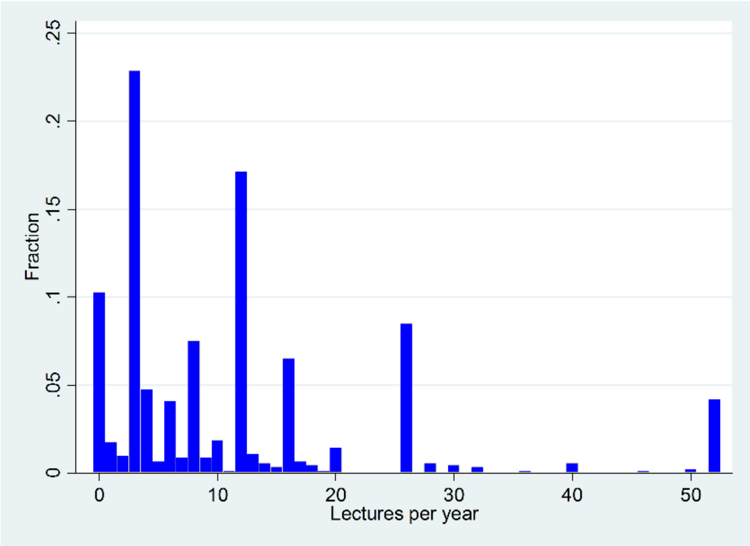
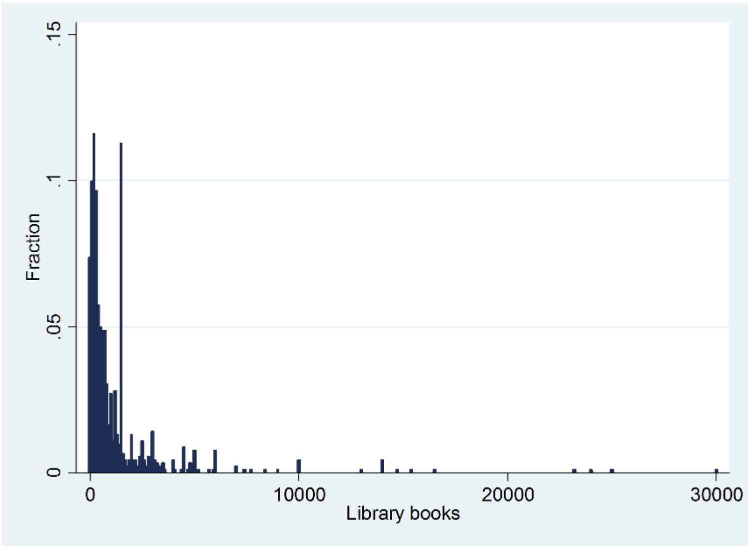


Figure 2.4: Core KAIs: histogram of library books across KAIs in 1851 (excluding KAIs with more than 50,000 library books)



In the year of 1851, around 15,000 lectures were held at core KAIs and close to two million volumes held in their libraries[23]. Figures 2.2 and 2.3 displays histograms of core KAIs

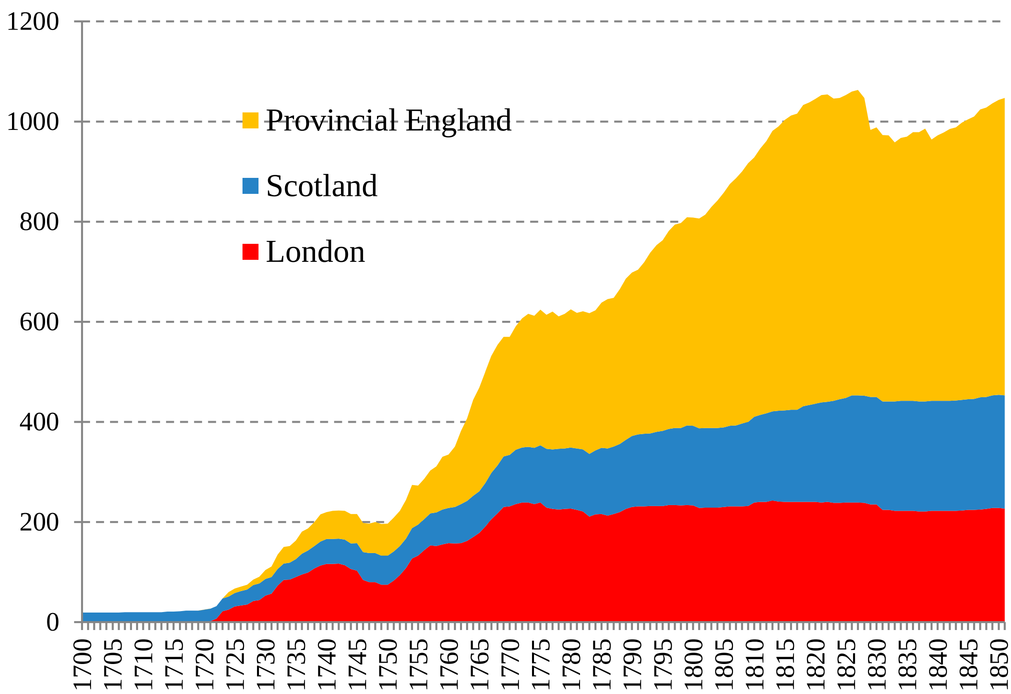
[23] Based on my classification of core KAIs and calculations based on the 1851 Census of Education.

by lectures per year and volumes in library respectively, in 1851. Lectures were most commonly held between once a quarter or once a month, though 10% of core KAIs did not hold lectures at all and more than 20% held lectures more regularly than monthly. A small number of core KAIs had very large libraries indeed, holding more than 10,000 volumes, though most held less than 3,000.

Peripheral KAIs

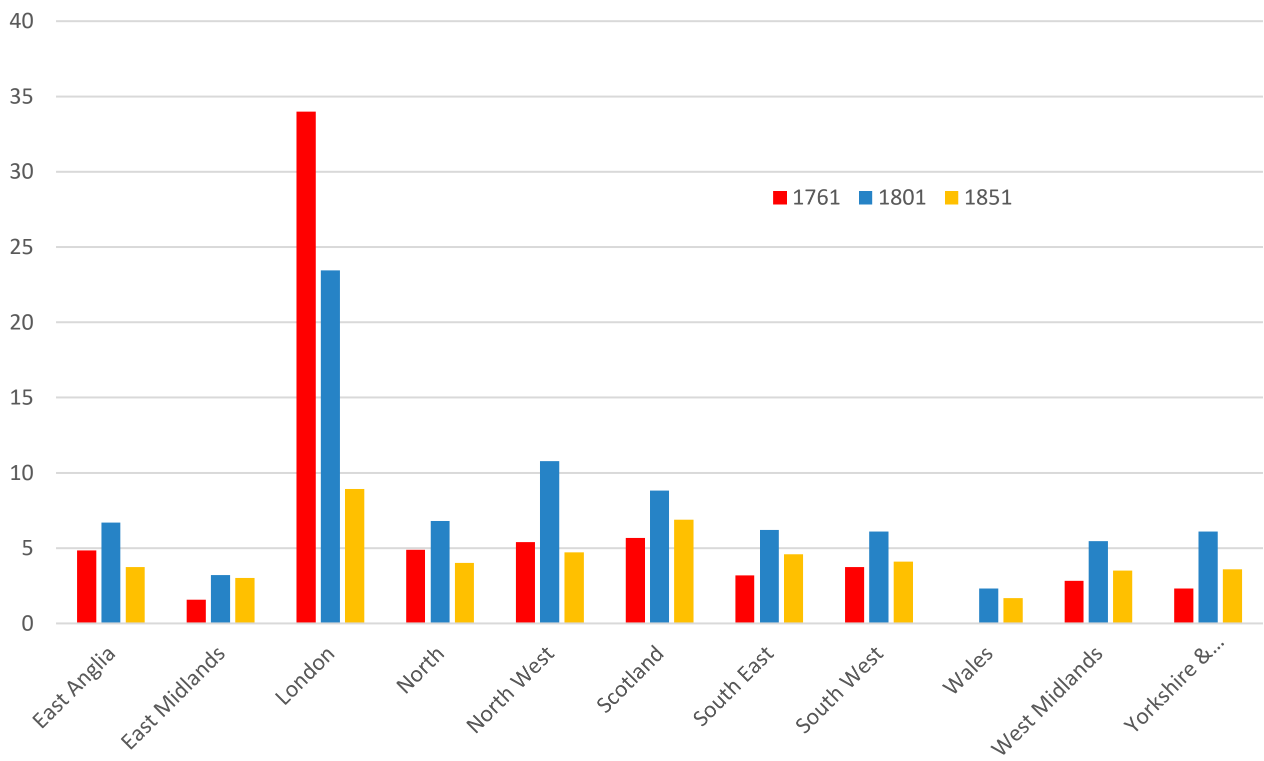
Masonic lodges: Although Freemasonry was by far the largest national social institution in eighteenth century Britain its economic impacts have been hardly studied (Clark 2000). However, Margaret Jacob (1991) and Paul A. Elliott (2010) have described its links to scientific culture in the eighteenth century, visible by the disproportionate number of 'men of science' among its membership, the occasional holding of scientific lectures at lodges and by written testimony to a masonic culture of science. Science, however casual the masons' interest in it was, was a natural fit for an institution that was constitutionally non-political and non-religious. The main role of Freemasonry in the KAI system was to augment the core KAI network. The masonic network was dense, national, cross-occupational and reached across social classes, increasing the *connectivity* of the British social structure.

Figure 2.5: Masonic Lodges in Great Britain, 1700-1853, London and Provincial



Historical data on Masonic lodges for the eighteenth and nineteenth centuries is available at *Lane's Masonic Records 1717-1894* (http://www.hrionline.ac.uk/lane/), an official Masonic website. I extract the data from this database to create a spatial dataset of all Masonic lodges in existence between 1700 and 1851, utilising their foundation and expiry dates. The first 'Grand Lodge' was founded in London in 1717, after four existing London lodges joined together. The movement then grew rapidly, first in London and later in the provinces, as chart 2.5 shows. By 1767, there were 440 lodges in England, 206 in London and 234 in the provinces, the number of provincial lodges overtaking metropolitan lodges in 1763. By 1850, there were 817 lodges in England, 225 of which were in London and 592 in the provinces. Figure 2.6 illustrates the regional perspective in 1761, 1801 and 1851, capturing the wide regional diffusion by 1801. Per capita ratios in all regions fell between 1801 and 1851, although the absolute numbers of lodges in each region continued to grow healthily. In terms of membership numbers, Peter Clark has surveyed around thirty lodges over the second half of the eighteenth century. He finds average membership numbers in London rising from around 30 in 1768-70 to about 75 in the 1780s and 1790s. He finds average membership numbers in provincial lodges of around 25 in 1768-70. As such, there were possibly close to 50,000 Freemasons in Britain by 1800.

Figure 2.6: Masonic Lodges per 100,000 Capita by British Region, 1761, 1801 & 1851



Public libraries: Britain's libraries prior to 1850 have been heroically catalogued by the late Robin Alston, Professor of Library Studies at University College London until retirement in 1998. Consulting over 1,500 published works over many years, he found references to over 30,000 private and public libraries in Great Britain. This section is based on his database, which lists the name of library, category, year of first mention and location (typically at the parish or sub parish level.[24]

Table 2.2: Libraries by Type in Great Britain, Founded up to 1850

Type	Count	%
Circulating Libraries	5,481	44.54
Endowed, Grammar & Charity Schools	1,846	15
Book Clubs & Reading Societies	1,183	9.61
Parochial Libraries	1,162	9.44
Subscription Libraries	1,005	8.17
Libraries of Societies	923	7.5
Mechanics' Institutions	538	4.37
Literary Societies	525	4.27
Chained libraries	306	2.49
Religious Libraries	191	1.55
Religious Subscription Libraries	117	0.95
Hospitals & Infirmaries	105	0.85
College Libraries	97	0.79
Sunday School Libraries	90	0.73
Professional Societies	89	0.72
Medical Libraries	85	0.69
Musical Circulating Libraries	48	0.39
Law Libraries	46	0.37
Science & Technology Libraries	43	0.35
Government Libraries	32	0.26
Cathedral Libraries	30	0.24
Agricultural Libraries	28	0.23
Factory & Shop Libraries	26	0.21
Cooperative Society Libraries	23	0.19
Public Libraries	21	0.17
Museum Libraries	20	0.16
Coffee House Libraries	15	0.12
Private Clubs	13	0.11
Juvenile Circulating Libraries	10	0.08
University Libraries	10	0.08
Inn Libraries	4	0.03
Record Offices	3	0.02
Itinerating Libraries	2	0.02
Religious Circulating Libraries	1	0.01
Juvenile Subscription Libraries	1	0.01

[24] It is available in pdf form at http://digitalriffs.blogspot.co.uk/2011/08/robin-alstons-library-history-database.html , and there appear to be plans to host it at the at the University of London, Institute for Historical Research's website at some point in the future.

Alston's data illustrates a proliferation of public libraries in eighteenth century Britain and a change in mix by type of public library as the century progressed. The library types in Alston's database are shown in table 2.2, along with overall counts by type. At the beginning of the century the landscape was dominated by parochial (church) libraries and the endowed libraries of large wealthy schools. This public infrastructure in turn was similar in aggregate size to the count of private libraries held in grand houses. However, the 1720s saw the start of the circulating library movement, which was followed in the second half of the century by the rise of subscription libraries. These libraries were more inclusive and provided significantly cheaper access to books than the alternative option of purchasing them. In the late eighteenth century, the average annual subscription for circulating and subscription libraries was approximately equal to the price of one book and members tended to borrow on average around twenty books per year (Kelly 1992).

Figures 2.7 and 2.8 display a time-series of public and private libraries based on Alston's database, first in absolute and then in per capita terms. The series is defined by the year of first mention in the literature that Alston surveyed, so does not necessarily reflect the year of foundation, although Alston reports that in about 50% of cases for public libraries it does. Nor does the database include an expiry date for library closures. As such, I show the flow of first mentions (based on a ten-year moving average) as opposed to the cumulative stock of first mentions. A striking feature of figures 2.7 and 2.8 is the surge of new public libraries during the second half of the eighteenth century relative to new private libraries. Beforehand, public and private libraries had grown at a similar rate, at around ten per decade until the late seventeenth century when they accelerated in unison to about twenty per decade. However, by the turn of the nineteenth century, new public libraries had surged to about one hundred per decade, and by mid-century to about two-hundred per decade. Given the much lower cost of book consumption provided by circulating and subscribing libraries, this acceleration must have significantly reduced the cost of codified access to knowledge. Figure 2.9 shows the stock of all public libraries mentioned in Alston's database by region in per capita terms up until 1761, 1801 and 1851.

Figure 2.7: Public and Private Libraries in Great Britain, Year of Foundation/First Mention, 1700-1850 (10y MA)

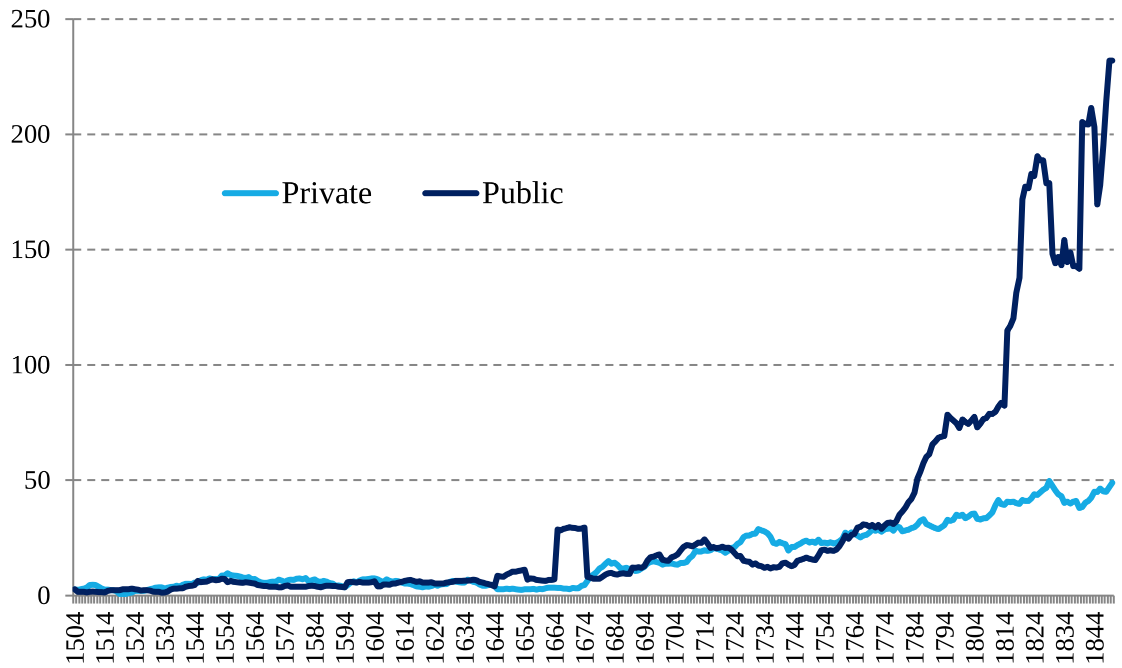


Figure 2.8: Public and Private Libraries in Great Britain <u>per 100,000 Capita</u>, Year of Foundation/First Mention, 1700-1850 (10y MA)

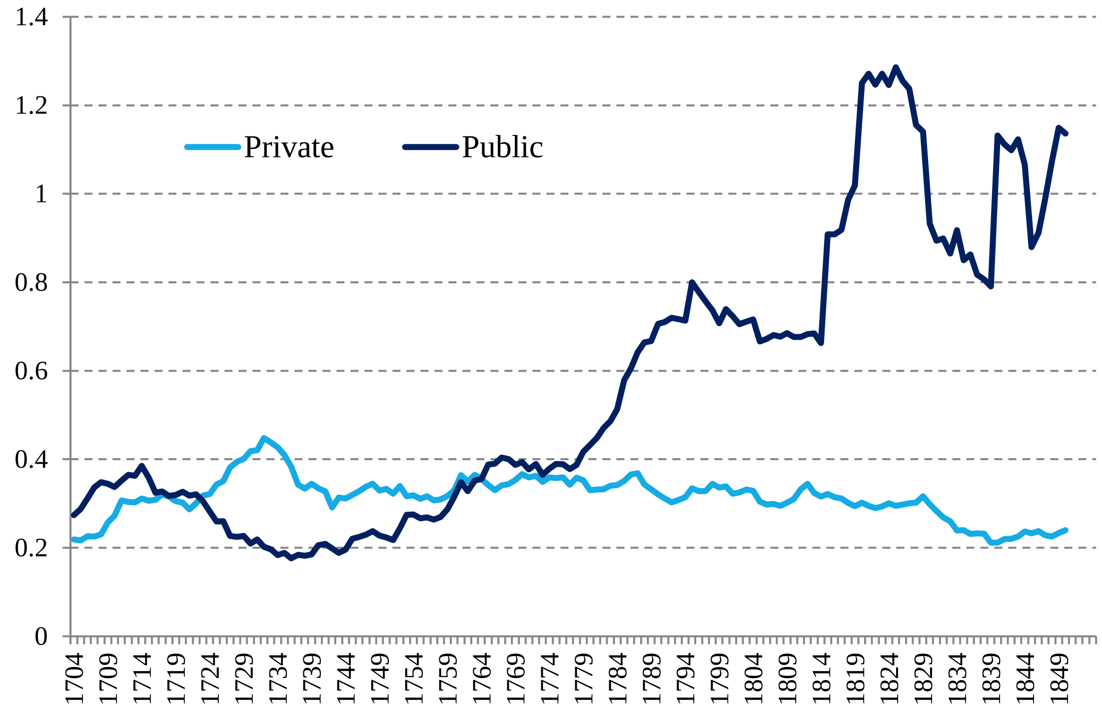
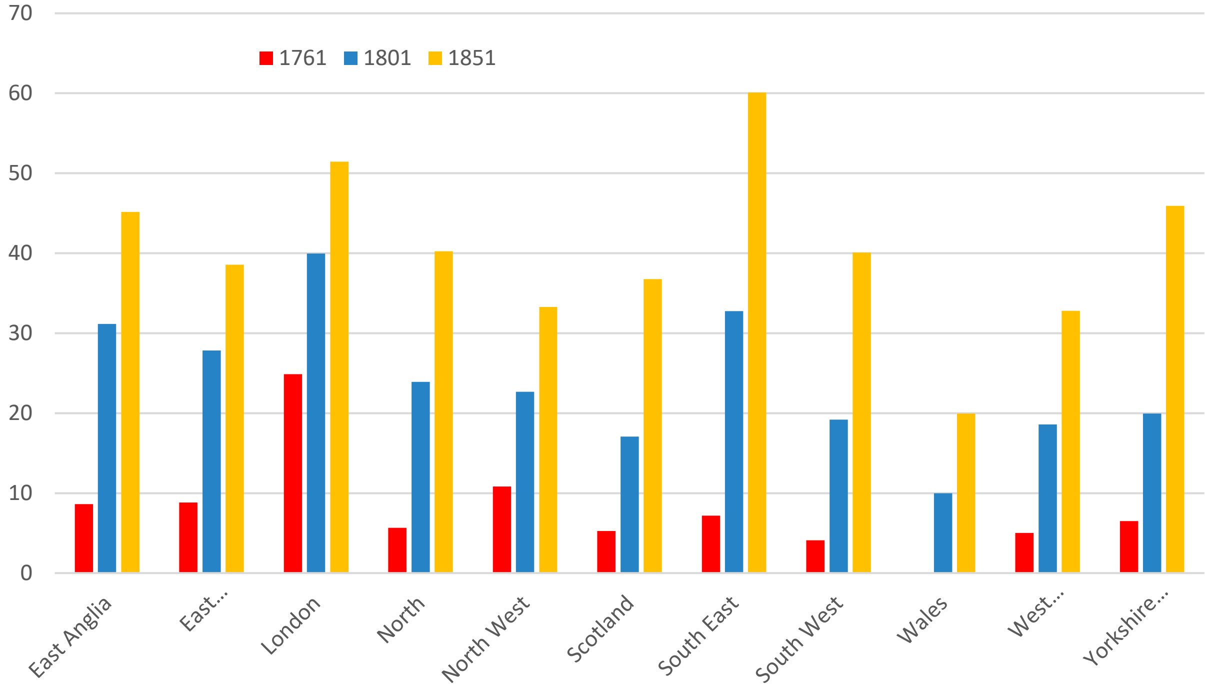


Figure 2.9: Public Libraries by 100,000 Capita British Region, 1761, 1801, 1851



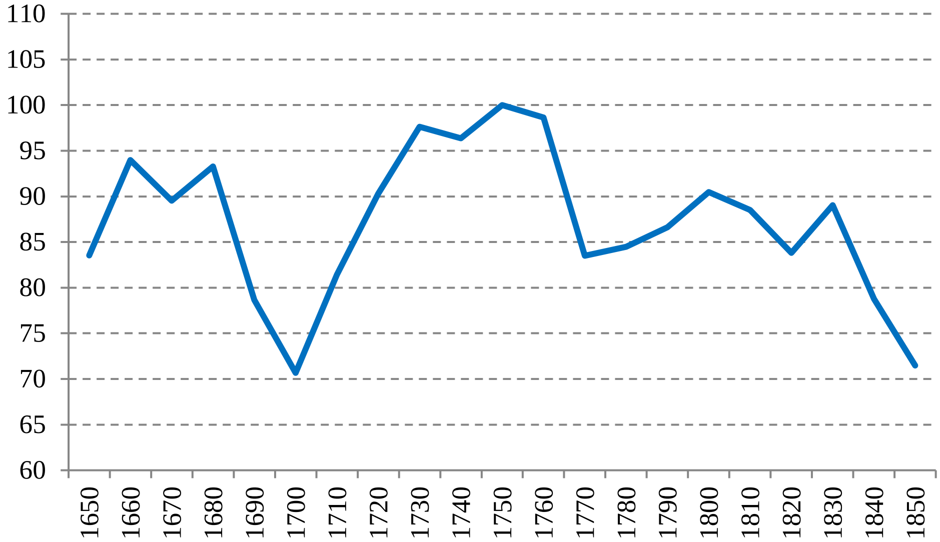
Booksellers: a proliferation of booksellers and reduction in book prices also contributed to falling knowledge access costs. The final lapse of the Licensing of the Press Act in 1694 deregulated the printing industry and set the stage for a national explosion in print during the eighteenth century. 'Print culture' under a relatively free press facilitated the diffusion of the 'popular Enlightenment' via newspapers, magazines, pamphlets and books (e.g. Porter 2000). Only a small fraction of publications would have been concerned with science or technology. Nevertheless, in absolute terms, this small fraction would have constituted a significant flow of scientific and technological literature. During the nineteenth century, printing costs fell significantly, particularly on large-run publications such as newspapers, as steam-power was harnessed within the printing process, as pioneered by William Chambers in Edinburgh (Fyfe 2006). As chart 2.10 shows, based on Greg Clark's cost of living index (Clark 2004), using a smoothed three-decade average, the real price of books fell by 30% between 1750 and 1850.

The *British Book Trade Index* project based at Oxford University[25] maintains a database of the English and Welsh book trade up to 1850. The *Scottish Book Trade Index* project extends this database to Scotland[26]. These databases contain information on all known members of the

[25] See http://bbti.bodleian .ox.ac.uk/
[26] http://www.nls.uk/catalogues/scottish-book-trade-index

book trade by occupation, year of known activity and location. I construct from them a panel dataset of booksellers in Great Britain between 1500 and 1851. The resultant national aggregate time series is shown in figure 2.11 and regional counts in 1761, 1801 and 1851 are displayed in figure 2.12. There is an explosion in the number of booksellers in existence around the second half of the eighteenth century, most of the increase being provincial. This must have helped to reduce the cost of access to codified knowledge, alongside the rapid growth of public libraries and the 30% reduction in book purchase costs. The regional perspective shows quite balanced coverage across all British regions by 1801.

Figure 2.10: Real price of books 1650-1850 (deflated by builders' wages, 3 decade centred average, 1750 = 100) Based on Clark (2004)



Finally, in figures 2.13 to 2.15, I provide maps of the county distributions of KAIs per capita, by type, in 1761, 1801 and 1851 respectively. In tables 2.3 and 2.4, I provide raw data on the counts of KAIs by county in 1761, 1801 and 1851, in absolute terms and per capita terms respectively. In table 2.5, I produce standardised scores for each county in terms of core KAIs and peripheral KAIs per capita in years 1761, 1801 and 1851. For each year, I express the raw count per capita for each county in standard deviation terms with respect to the cross section. I do this for core and peripheral KAIs separately to produce two separate scores. To construct a single peripheral KAI standardised score, I take an average of the three standardised scores for Masonic Lodges, public libraries and booksellers. Figure 2.16 illustrates the geographical correlation between the core and peripheral parts of the infrastructure, via a scatter plot of standardised core and standardised peripheral scores by county in 1851.

Figure 2.11: Booksellers in Great Britain, 1500-1850, London Edinburgh and Provincial

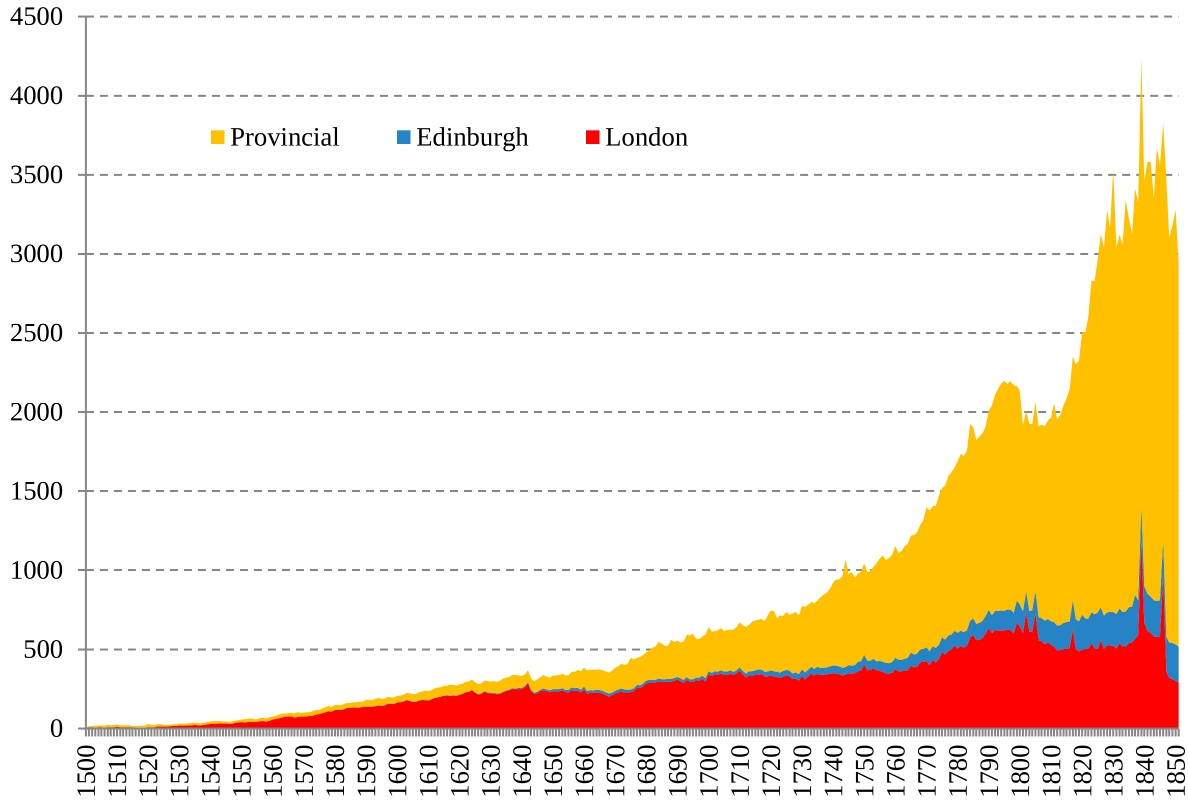


Figure 2.12: Booksellers per 100,000 Capita by British Region, 1761, 1801, 1851

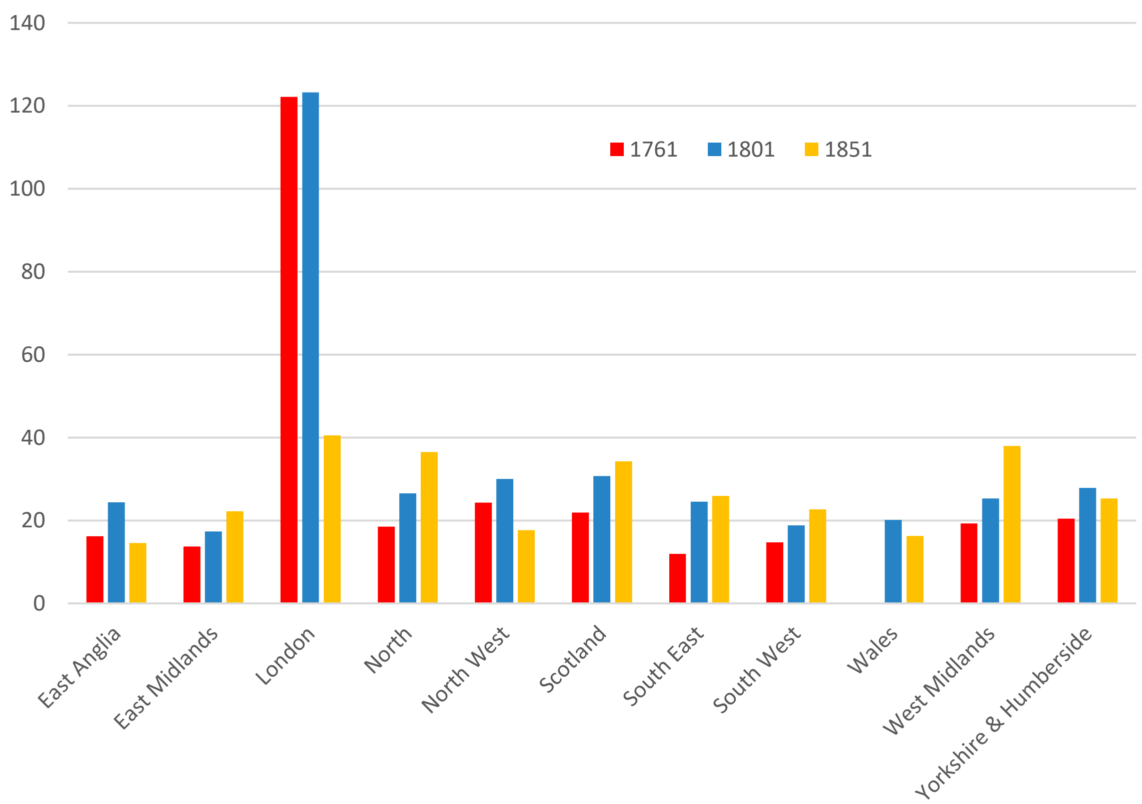


Figure 2.13: KAIs Per Capita <u>1761</u>

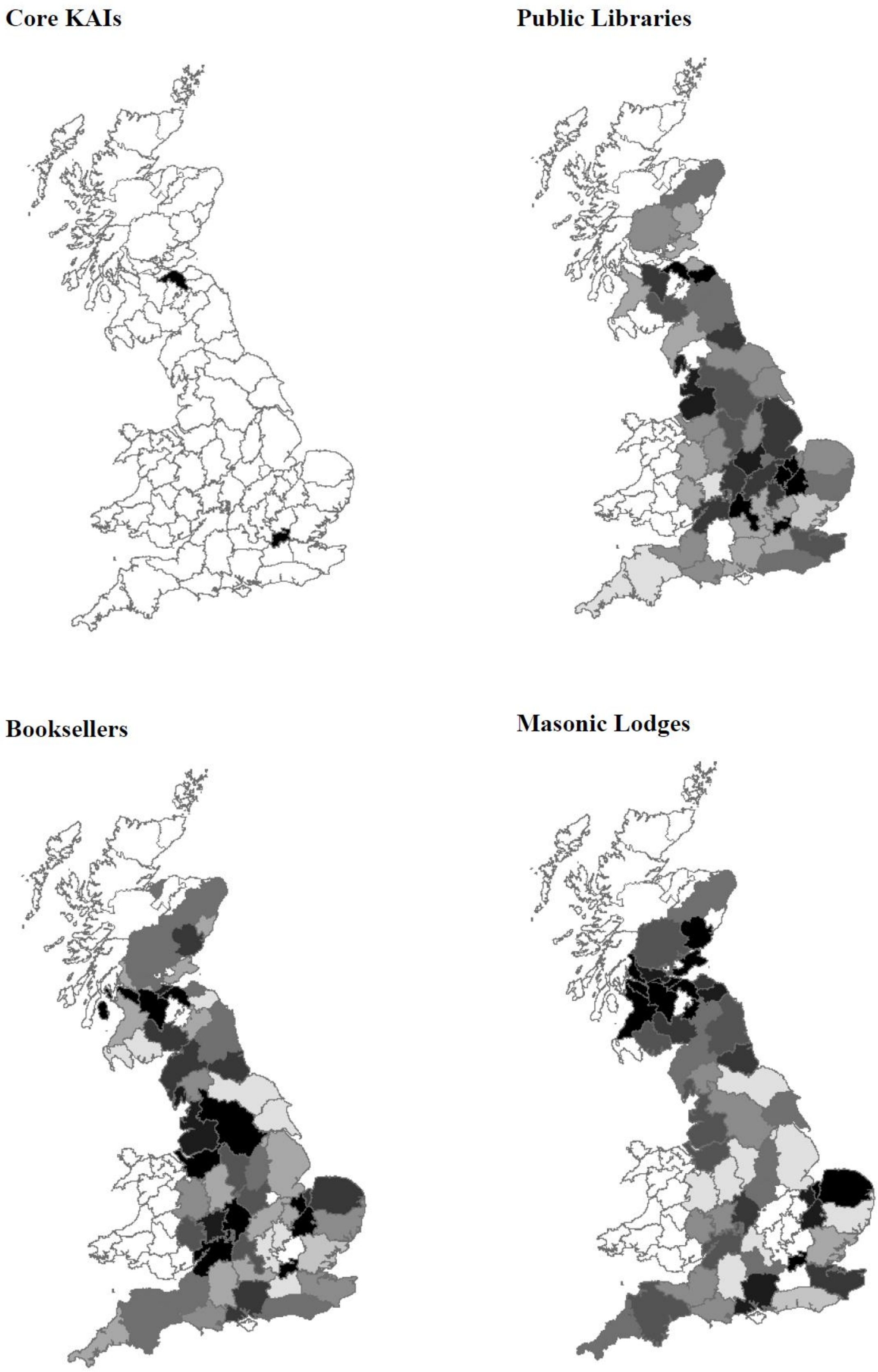
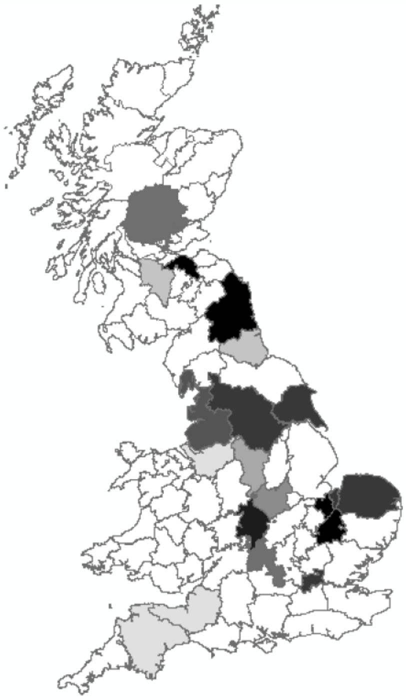
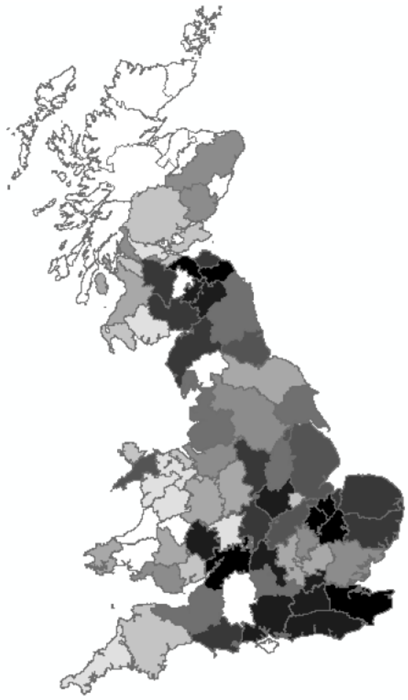


Figure 2.14: KAIs Per Capita 1801

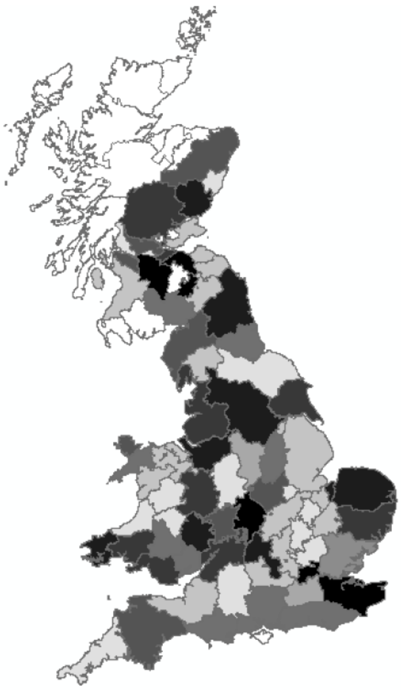
Core KAIs



Public Libraries



Booksellers



Masonic Lodges

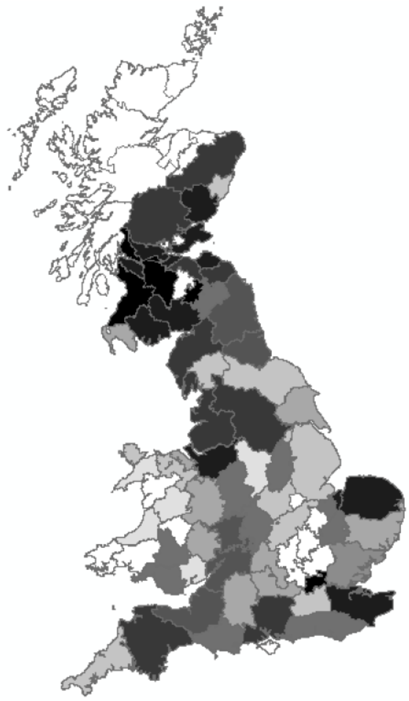


Figure 2.15: KAIs Per Capita <u>1851</u>

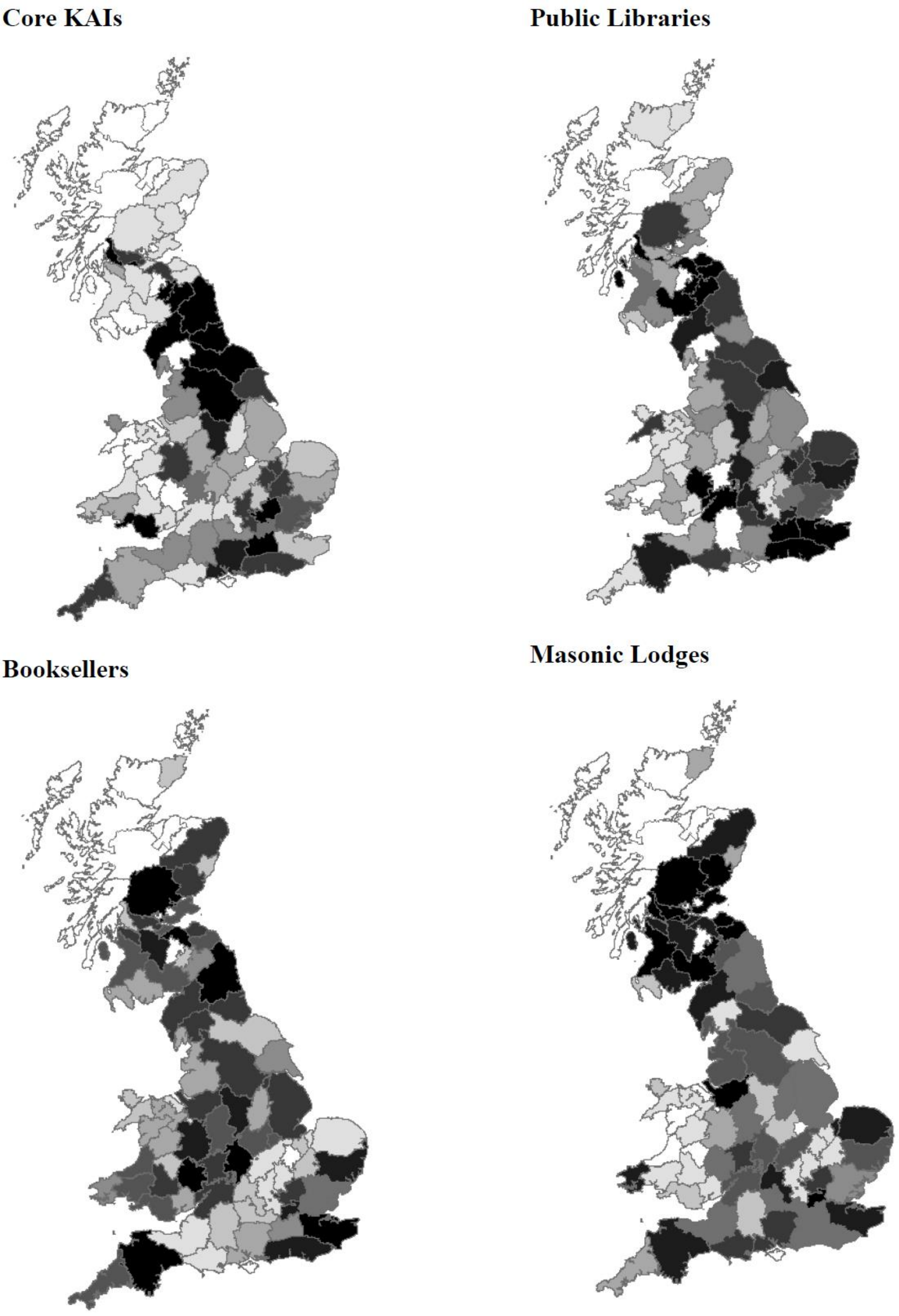


Table 2.3: KAIs by county, 1761, 1801 and 1851

County & Country		Core 1761	Core 1801	Core 1851	Libraries 1761	Libraries 1801	Libraries 1851	Booksellers 1761	Booksellers 1801	Booksellers 1851	Freemasons 1761	Freemasons 1801	Freemasons 1851
BEDFORDSHIRE	E	0	0	5	5	12	33	3	7	1	0	0	2
BERKSHIRE	E	0	0	9	3	32	87	13	16	24	3	6	6
BUCKINGHAMSHIRE	E	0	0	8	3	15	27	6	16	3	0	0	2
CAMBRIDGESHIRE	E	0	3	11	25	47	85	24	16	13	6	5	3
CHESHIRE	E	0	1	15	7	34	162	35	64	121	7	26	38
CORNWALL	E	0	0	23	1	13	66	10	19	66	6	5	10
CUMBERLAND	E	0	0	14	3	36	102	18	30	67	3	9	12
DERBYSHIRE	E	0	1	18	9	42	130	22	26	94	2	3	6
DEVON	E	0	2	25	7	40	304	43	85	274	15	30	35
DORSET	E	0	0	6	5	33	80	14	22	5	2	6	8
DURHAM	E	0	1	29	11	43	156	26	34	115	8	11	15
EAST RIDING	E	0	2	16	5	28	147	6	33	43	3	5	3
ESSEX	E	0	0	17	5	43	143	13	40	62	4	10	10
GLOUCESTERSHIRE	E	0	0	9	22	103	287	52	59	146	12	15	16
HAMPSHIRE	E	0	0	26	7	72	159	36	48	53	15	16	18
HEREFORDSHIRE	E	0	0	0	3	25	63	16	24	57	2	3	3
HERTFORDSHIRE	E	0	0	13	3	17	71	0	11	40	0	0	8
HUNTINGDONSHIRE	E	0	0	3	7	20	32	4	3	0	0	0	1
KENT	E	0	0	19	20	119	420	32	120	275	15	40	39
LANCASHIRE	E	0	7	95	41	164	678	73	198	325	17	68	81
LEICESTERSHIRE	E	0	1	10	14	46	88	21	30	50	3	4	6
LINCOLNSHIRE	E	0	0	17	16	55	148	20	27	129	1	6	14
LONDON	E	2	16	120	139	414	1312	683	1277	1034	190	243	228
NORFOLK	E	0	4	15	14	80	193	55	79	6	23	31	24
NORTH RIDING	E	0	0	22	6	19	85	8	11	22	2	4	8
NORTHAMPTONSHIRE	E	0	0	8	12	36	76	9	21	1	0	4	8
NORTHUMBERLAND	E	0	4	27	8	37	132	23	59	154	7	12	11
NOTTINGHAMSHIRE	E	0	0	9	4	36	106	15	30	38	4	8	9
OXFORDSHIRE	E	0	1	3	28	45	83	18	36	7	1	5	9
RUTLAND	E	0	0	0	1	2	3	0	1	5	0	0	0
SHROPSHIRE	E	0	0	13	5	26	77	18	50	88	2	8	7
SOMERSET	E	0	1	21	13	66	154	32	47	5	6	18	16
STAFFORDSHIRE	E	0	0	26	8	35	137	18	28	116	2	15	20
SUFFOLK	E	0	0	15	13	66	164	24	62	118	3	9	13
SURREY	E	0	0	14	5	41	215	8	20	33	0	3	7
SUSSEX	E	0	0	19	7	58	255	19	34	146	2	8	12
WARWICKSHIRE	E	0	5	20	14	68	268	42	82	329	9	12	19
WEST RIDING	E	0	6	152	28	123	571	109	193	377	9	43	52
WESTMORLAND	E	0	0	0	0	0	0	5	6	18	1	1	1
WILTSHIRE	E	0	0	11	0	0	0	22	18	8	3	7	6
WORCESTERSHIRE	E	0	0	12	2	6	17	29	34	61	3	9	11
Aberdeen	S	0	0	3	7	23	77	19	28	73	4	10	16
Argyll	S	0	0	0	0	0	0	0	0	0	0	0	0
Ayr	S	0	0	5	2	13	77	6	15	38	5	19	26
Banff	S	0	0	0	0	0	0	0	0	0	0	0	0
Berwick	S	0	0	1	4	13	31	1	5	7	2	3	4
Bute	S	0	0	0	0	2	11	2	2	3	0	0	1
Caithness	S	0	0	0	0	0	4	0	0	2	0	0	1
Clackmannan	S	0	0	0	0	0	0	0	0	0	0	0	0
Dumbarton	S	0	0	4	0	4	28	1	2	4	2	4	6
Dumfries	S	0	0	2	3	16	46	9	11	17	3	8	11
Edinburgh	S	1	3	14	29	75	217	102	180	345	9	12	18
Elgin	S	0	0	0	0	0	0	0	0	0	0	0	0

Fife	S	0	0	3	3	10	59	9	14	28	10	12	16
Forfar	S	0	0	6	2	21	57	16	34	64	7	11	18
Haddington	S	0	0	1	1	9	27	5	5	11	2	3	3
Inverness	S	0	0	0	0	0	0	0	0	0	0	0	0
Kincardine	S	0	0	0	0	0	0	2	3	3	0	1	1
Kinross	S	0	0	0	0	0	0	0	0	0	0	0	0
Kirkcudbright	S	0	0	0	0	2	16	1	1	6	1	3	3
Lanark	S	0	1	17	8	43	185	56	109	211	10	23	33
Linlithgow	S	0	0	1	0	2	8	4	5	6	2	2	2
Nairn	S	0	0	0	0	0	2	1	0	0	0	0	0
Orkney	S	0	0	0	0	0	0	0	0	0	0	0	0
Peebles	S	0	0	0	0	0	0	0	0	0	0	0	0
Perth	S	0	1	2	5	13	58	18	36	77	6	11	13
Renfrew	S	0	0	7	0	8	60	12	18	48	3	8	12
Ross & Cromarty	S	0	0	0	0	0	0	0	0	0	0	0	0
Roxburgh	S	0	0	5	2	11	35	3	4	8	1	2	2
Selkirk	S	0	0	1	0	2	9	0	2	1	1	1	3
Stirling	S	0	0	5	0	2	31	6	12	21	3	6	7
Sutherland	S	0	0	0	0	0	3	0	0	0	0	0	0
Wigton	S	0	0	0	0	2	9	1	1	6	0	1	1
ANGLESEY	W	0	0	2	0	2	8	1	6	4	0	1	1
BRECKNOCKSHIRE	W	0	0	2	1	6	16	3	7	14	2	2	1
CARDIGANSHIRE	W	0	0	2	0	1	19	0	6	18	0	1	0
CARMARTHENSHIRE	W	0	0	4	0	0	0	9	16	21	1	0	1
CARNARVONSHIRE	W	0	0	0	8	12	43	4	10	9	0	1	2
DENBIGHSHIRE	W	0	0	3	1	4	11	10	11	12	0	2	1
FLINTSHIRE	W	0	0	0	2	2	10	0	4	1	1	1	0
GLAMORGANSHIRE	W	0	0	19	3	16	66	6	21	55	3	4	6
MERIONETHSHIRE	W	0	0	0	0	2	8	0	5	7	0	0	0
MONMOUTHSHIRE	W	0	0	6	1	6	25	4	12	26	1	1	3
MONTGOMERYSHIRE	W	0	0	1	0	2	6	6	6	10	0	1	1
PEMBROKESHIRE	W	0	0	3	3	7	22	0	15	15	1	0	4
RADNORSHIRE	W	0	0	0	0	0	3	1	2	1	0	0	0

Table 2.4: KAIs per 100,000 capita by county, 1761, 1801 and 1851

		Core			Libraries			Booksellers			Freemasons		
County & Country		1761	1801	1851	1761	1801	1851	1761	1801	1851	1761	1801	1851
BEDFORDSHIRE	E	0.0	0.0	3.9	9.5	18.1	25.4	5.7	10.6	0.8	0.0	0.0	1.5
BERKSHIRE	E	0.0	0.0	4.5	3.0	24.4	43.7	12.9	12.2	12.0	3.0	4.6	3.0
BUCKINGHAMSHIRE	E	0.0	0.0	5.6	3.1	15.7	18.8	6.2	16.7	2.1	0.0	0.0	1.4
CAMBRIDGESHIRE	E	0.0	3.3	5.7	32.0	51.8	44.3	30.8	17.6	6.8	7.7	5.5	1.6
CHESHIRE	E	0.0	0.5	3.5	5.0	18.0	38.3	24.9	33.8	28.6	5.0	13.7	9.0
CORNWALL	E	0.0	0.0	6.4	0.8	6.7	18.5	7.5	9.8	18.5	4.5	2.6	2.8
CUMBERLAND	E	0.0	0.0	7.2	3.4	30.7	52.2	20.3	25.6	34.3	3.4	7.7	6.1
DERBYSHIRE	E	0.0	0.7	6.9	7.9	29.8	49.9	19.3	18.4	36.1	1.8	2.1	2.3
DEVON	E	0.0	0.6	4.4	2.3	11.7	53.1	14.0	24.8	47.9	4.9	8.8	6.1
DORSET	E	0.0	0.0	3.4	5.0	30.1	45.2	14.0	20.1	2.8	2.0	5.5	4.5
DURHAM	E	0.0	0.6	7.0	8.5	27.0	37.9	20.2	21.4	27.9	6.2	6.9	3.6
EAST RIDING	E	0.0	1.6	6.3	4.8	22.0	57.8	5.7	25.9	16.9	2.9	3.9	1.2
ESSEX	E	0.0	0.0	4.9	2.5	20.4	41.6	6.5	19.0	18.0	2.0	4.8	2.9
GLOUCESTERSHIRE	E	0.0	0.0	2.1	10.2	45.0	68.4	24.1	25.8	34.8	5.6	6.6	3.8
HAMPSHIRE	E	0.0	0.0	6.5	3.9	33.1	39.6	20.2	22.0	13.2	8.4	7.3	4.5
HEREFORDSHIRE	E	0.0	0.0	0.0	3.7	33.2	63.6	19.5	31.9	57.5	2.4	4.0	3.0
HERTFORDSHIRE	E	0.0	0.0	7.5	3.1	16.7	40.8	0.0	10.8	23.0	0.0	0.0	4.6
HUNTINGDONSHIRE	E	0.0	0.0	5.0	19.9	57.6	53.1	11.4	8.6	0.0	0.0	0.0	1.7
KENT	E	0.0	0.0	3.9	8.5	46.0	86.6	13.5	46.4	56.7	6.3	15.5	8.0
LANCASHIRE	E	0.0	1.0	4.5	13.5	24.0	32.3	24.1	29.0	15.5	5.6	10.0	3.9
LEICESTERSHIRE	E	0.0	0.7	4.3	13.4	34.3	37.5	20.1	22.4	21.3	2.9	3.0	2.6
LINCOLNSHIRE	E	0.0	0.0	4.2	8.8	26.8	37.0	11.0	13.1	32.2	0.6	2.9	3.5
LONDON	E	0.4	1.5	4.7	24.9	39.9	51.4	122.2	123.2	40.5	34.0	23.4	8.9
NORFOLK	E	0.0	1.5	3.5	5.6	29.5	44.5	21.9	29.1	1.4	9.1	11.4	5.5
NORTH RIDING	E	0.0	0.0	11.3	4.3	12.9	43.7	5.8	7.4	11.3	1.4	2.7	4.1
NORTHAMPTONSHIRE	E	0.0	0.0	3.7	9.6	28.1	35.5	7.2	16.4	0.5	0.0	3.1	3.7

NORTHUMBERLAND	E	0.0	2.4	8.9	6.0	22.0	43.5	17.1	35.1	50.7	5.2	7.1	3.6
NOTTINGHAMSHIRE	E	0.0	0.0	3.1	4.3	23.6	36.0	16.0	19.7	12.9	4.3	5.2	3.1
OXFORDSHIRE	E	0.0	0.9	1.8	29.2	40.1	48.8	18.8	32.1	4.1	1.0	4.5	5.3
RUTLAND	E	0.0	0.0	0.0	6.3	10.9	12.4	0.0	5.5	20.6	0.0	0.0	0.0
SHROPSHIRE	E	0.0	0.0	5.3	3.7	14.2	31.4	13.3	27.4	35.9	1.5	4.4	2.9
SOMERSET	E	0.0	0.4	4.6	5.7	23.4	33.8	14.0	16.7	1.1	2.6	6.4	3.5
STAFFORDSHIRE	E	0.0	0.0	4.1	5.1	13.8	21.7	11.4	11.0	18.4	1.3	5.9	3.2
SUFFOLK	E	0.0	0.0	4.5	7.4	30.7	48.8	13.6	28.9	35.1	1.7	4.2	3.9
SURREY	E	0.0	0.0	6.9	3.0	37.4	106.2	4.8	18.3	16.3	0.0	2.7	3.5
SUSSEX	E	0.0	0.0	5.6	6.8	36.0	75.1	18.4	21.1	43.0	1.9	5.0	3.5
WARWICKSHIRE	E	0.0	2.3	4.2	9.9	31.5	55.8	29.6	37.9	68.5	6.3	5.6	4.0
WEST RIDING	E	0.0	1.0	11.7	7.8	21.3	43.9	30.5	33.5	29.0	2.5	7.5	4.0
WESTMORLAND	E	0.0	0.0	0.0	0.0	0.0	0.0	13.5	14.7	30.8	2.7	2.4	1.7
WILTSHIRE	E	0.0	0.0	4.6	0.0	0.0	0.0	11.5	10.4	3.3	1.6	4.0	2.5
WORCESTERSHIRE	E	0.0	0.0	4.6	1.7	4.5	6.6	24.0	25.7	23.6	2.5	6.8	4.3
Aberdeen	S	0.0	0.0	1.4	6.0	19.0	36.3	16.4	23.1	34.4	3.4	8.3	7.5
Argyll	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ayr	S	0.0	0.0	2.6	3.4	15.4	40.6	10.2	17.8	20.0	8.5	22.6	13.7
Banff	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Berwick	S	0.0	0.0	2.8	16.7	43.0	85.4	4.2	16.6	19.3	8.3	9.9	11.0
Bute	S	0.0	0.0	0.0	0.0	17.0	66.2	28.1	17.0	18.1	0.0	0.0	6.0
Caithness	S	0.0	0.0	0.0	0.0	0.0	10.3	0.0	0.0	5.2	0.0	0.0	2.6
Clackmannan	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dumbarton	S	0.0	0.0	8.9	0.0	19.3	62.1	7.2	9.7	8.9	14.4	19.3	13.3
Dumfries	S	0.0	0.0	2.6	7.5	29.3	58.9	22.6	20.1	21.8	7.5	14.7	14.1
Edinburgh	S	1.1	2.4	5.4	32.1	61.2	83.6	112.8	146.8	133.0	10.0	9.8	6.9
Elgin	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fife	S	0.0	0.0	2.0	3.7	10.7	38.4	11.0	14.9	18.2	12.3	12.8	10.4
Forfar	S	0.0	0.0	3.1	2.9	21.2	29.8	23.2	34.3	33.5	10.2	11.1	9.4
Haddington	S	0.0	0.0	2.7	3.4	30.0	74.2	16.8	16.7	30.2	6.7	10.0	8.2

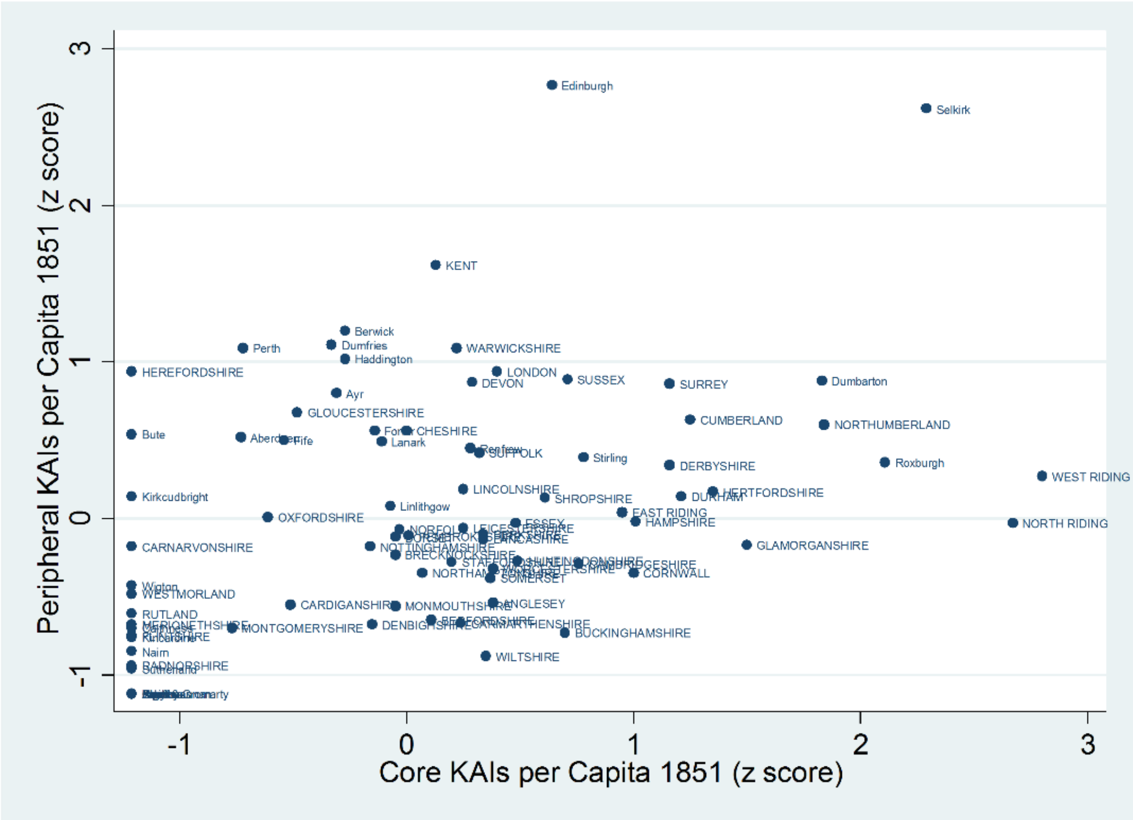
Inverness	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kincardine	S	0.0	0.0	0.0	0.0	0.0	0.0	8.7	11.4	8.7	0.0	3.8	2.9
Kinross	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kirkcudbright	S	0.0	0.0	0.0	0.0	6.8	37.1	4.7	3.4	13.9	4.7	10.3	7.0
Lanark	S	0.0	0.7	3.2	9.8	29.1	34.9	68.5	73.8	39.8	12.2	15.6	6.2
Linlithgow	S	0.0	0.0	3.3	0.0	11.2	26.5	23.8	28.0	19.9	11.9	11.2	6.6
Nairn	S	0.0	0.0	0.0	0.0	0.0	20.1	17.6	0.0	0.0	0.0	0.0	0.0
Orkney	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Peebles	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Perth	S	0.0	0.8	1.4	4.2	10.4	41.8	15.0	28.7	55.5	5.0	8.8	9.4
Renfrew	S	0.0	0.0	4.3	0.0	10.2	37.2	45.0	22.9	29.8	11.3	10.2	7.4
Ross & Cromarty	S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Roxburgh	S	0.0	0.0	9.7	5.8	32.6	67.8	8.6	11.9	15.5	2.9	5.9	3.9
Selkirk	S	0.0	0.0	10.2	0.0	37.1	91.8	0.0	37.1	10.2	24.9	18.6	30.6
Stirling	S	0.0	0.0	5.8	0.0	3.9	35.9	16.2	23.6	24.4	8.1	11.8	8.1
Sutherland	S	0.0	0.0	0.0	0.0	0.0	11.6	0.0	0.0	0.0	0.0	0.0	0.0
Wigton	S	0.0	0.0	0.0	0.0	8.7	20.7	6.1	4.4	13.8	0.0	4.4	2.3
ANGLESEY	W		0.0	4.6		7.8	18.5		23.4	9.3		3.9	2.3
BRECKNOCKSHIRE	W		0.0	3.4		17.2	27.0		20.1	23.7		5.7	1.7
CARDIGANSHIRE	W		0.0	2.0		1.6	19.5		9.8	18.4		1.6	0.0
CARMARTHENSHIRE	W		0.0	4.2		0.0	0.0		28.8	22.2		0.0	1.1
CARNARVONSHIRE	W		0.0	0.0		26.1	45.4		21.7	9.5		2.2	2.1
DENBIGHSHIRE	W		0.0	3.1		6.5	11.4		17.9	12.4		3.2	1.0
FLINTSHIRE	W		0.0	0.0		9.0	24.4		18.0	2.4		4.5	0.0
GLAMORGANSHIRE	W		0.0	7.9		21.6	27.5		28.3	22.9		5.4	2.5
MERIONETHSHIRE	W		0.0	0.0		5.6	15.6		13.9	13.6		0.0	0.0
MONMOUTHSHIRE	W		0.0	3.4		11.0	14.1		21.9	14.7		1.8	1.7
MONTGOMERYSHIRE	W		0.0	1.3		3.6	7.8		10.7	13.0		1.8	1.3
PEMBROKESHIRE	W		0.0	3.6		13.9	26.0		29.8	17.8		0.0	4.7
RADNORSHIRE	W		0.0	0.0		0.0	9.5		8.5	3.2		0.0	0.0

Table 2.5: Standardised KAI prevalence by county, 1761, 1801 and 1851

County	Country	Core 1761	Peripheral 1761	Core 1801	Peripheral 1801	Core 1851	Peripheral 1851
BEDFORDSHIRE	ENGLAND	-0.15	-0.25	-0.42	-0.51	0.11	-0.65
BERKSHIRE	ENGLAND	-0.15	-0.26	-0.42	-0.06	0.34	-0.10
BUCKINGHAMSHIRE	ENGLAND	-0.15	-0.54	-0.42	-0.47	0.70	-0.73
CAMBRIDGESHIRE	ENGLAND	-0.15	1.66	4.76	0.69	0.76	-0.29
CHESHIRE	ENGLAND	-0.15	0.15	0.41	0.70	0.00	0.56
CORNWALL	ENGLAND	-0.15	-0.36	-0.42	-0.61	1.00	-0.35
CUMBERLAND	ENGLAND	-0.15	-0.10	-0.42	0.48	1.25	0.63
DERBYSHIRE	ENGLAND	-0.15	0.00	0.69	0.01	1.16	0.34
DEVON	ENGLAND	-0.15	-0.16	0.50	0.11	0.29	0.87
DORSET	ENGLAND	-0.15	-0.20	-0.42	0.24	-0.05	-0.12
DURHAM	ENGLAND	-0.15	0.31	0.57	0.28	1.21	0.14
EAST RIDING	ENGLAND	-0.15	-0.30	2.04	0.06	0.95	0.04
ESSEX	ENGLAND	-0.15	-0.44	-0.42	-0.03	0.48	-0.03
GLOUCESTERSHIRE	ENGLAND	-0.15	0.41	-0.42	0.73	-0.48	0.68
HAMPSHIRE	ENGLAND	-0.15	0.22	-0.42	0.46	1.01	-0.02
HEREFORDSHIRE	ENGLAND	-0.15	-0.15	-0.42	0.40	-1.21	0.94
HERTFORDSHIRE	ENGLAND	-0.15	-0.64	-0.42	-0.54	1.35	0.17
HUNTINGDONSHIRE	ENGLAND	-0.15	0.33	-0.42	0.34	0.49	-0.27
KENT	ENGLAND	-0.15	0.21	-0.42	1.63	0.13	1.62
LANCASHIRE	ENGLAND	-0.15	0.57	1.19	0.52	0.34	-0.13
LEICESTERSHIRE	ENGLAND	-0.15	0.34	0.75	0.22	0.25	-0.06
LINCOLNSHIRE	ENGLAND	-0.15	-0.16	-0.42	-0.09	0.25	0.19
LONDON	ENGLAND	2.51	4.35	2.00	3.17	0.40	0.94
NORFOLK	ENGLAND	-0.15	0.37	1.89	0.74	-0.03	-0.07
NORTH RIDING	ENGLAND	-0.15	-0.40	-0.42	-0.51	2.67	-0.03
NORTHAMPTONSHIRE	ENGLAND	-0.15	-0.22	-0.42	0.00	0.07	-0.35
NORTHUMBERLAND	ENGLAND	-0.15	0.08	3.31	0.40	1.84	0.60
NOTTINGHAMSHIRE	ENGLAND	-0.15	-0.07	-0.42	0.08	-0.16	-0.18
OXFORDSHIRE	ENGLAND	-0.15	0.94	0.98	0.59	-0.61	0.01
RUTLAND	ENGLAND	-0.15	-0.49	-0.42	-0.75	-1.21	-0.61
SHROPSHIRE	ENGLAND	-0.15	-0.31	-0.42	-0.06	0.61	0.13
SOMERSET	ENGLAND	-0.15	-0.13	0.14	0.10	0.37	-0.38
STAFFORDSHIRE	ENGLAND	-0.15	-0.28	-0.42	-0.23	0.20	-0.28
SUFFOLK	ENGLAND	-0.15	-0.12	-0.42	0.32	0.32	0.42
SURREY	ENGLAND	-0.15	-0.56	-0.42	0.21	1.16	0.86
SUSSEX	ENGLAND	-0.15	-0.05	-0.42	0.36	0.71	0.89
WARWICKSHIRE	ENGLAND	-0.15	0.53	3.21	0.56	0.22	1.09
WEST RIDING	ENGLAND	-0.15	0.23	1.21	0.38	2.80	0.27
WESTMORLAND	ENGLAND	-0.15	-0.40	-0.42	-0.70	-1.21	-0.48
WILTSHIRE	ENGLAND	-0.15	-0.50	-0.42	-0.67	0.35	-0.88
WORCESTERSHIRE	ENGLAND	-0.15	-0.17	-0.42	-0.16	0.38	-0.32
Aberdeen	SCOTLAND	-0.15	-0.03	-0.42	0.22	-0.73	0.52
Argyll	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Ayr	SCOTLAND	-0.15	0.04	-0.42	0.94	-0.31	0.80

Banff	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Berwick	SCOTLAND	-0.15	0.55	-0.42	0.75	-0.27	1.20
Bute	SCOTLAND	-0.15	-0.32	-0.42	-0.44	-1.21	0.54
Caithness	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-0.70
Clackmannan	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Dumbarton	SCOTLAND	-0.15	0.18	-0.42	0.70	1.83	0.88
Dumfries	SCOTLAND	-0.15	0.38	-0.42	0.80	-0.33	1.11
Edinburgh	SCOTLAND	8.07	3.13	3.41	3.16	0.64	2.77
Elgin	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Fife	SCOTLAND	-0.15	0.29	-0.42	0.18	-0.54	0.50
Forfar	SCOTLAND	-0.15	0.33	-0.42	0.61	-0.14	0.56
Haddington	SCOTLAND	-0.15	0.04	-0.42	0.47	-0.27	1.02
Inverness	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Kincardine	SCOTLAND	-0.15	-0.64	-0.42	-0.67	-1.21	-0.76
Kinross	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Kirkcudbright	SCOTLAND	-0.15	-0.43	-0.42	-0.24	-1.21	0.14
Lanark	SCOTLAND	-0.15	1.51	0.64	1.68	-0.11	0.49
Linlithgow	SCOTLAND	-0.15	0.30	-0.42	0.30	-0.07	0.08
Nairn	SCOTLAND	-0.15	-0.49	-0.42	-1.08	-1.21	-0.85
Orkney	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Peebles	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Perth	SCOTLAND	-0.15	-0.05	0.83	0.14	-0.72	1.09
Renfrew	SCOTLAND	-0.15	0.61	-0.42	0.14	0.28	0.45
Ross & Cromarty	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-1.12
Roxburgh	SCOTLAND	-0.15	-0.20	-0.42	0.20	2.11	0.36
Selkirk	SCOTLAND	-0.15	0.68	-0.42	1.47	2.29	2.62
Stirling	SCOTLAND	-0.15	-0.04	-0.42	0.11	0.78	0.39
Sutherland	SCOTLAND	-0.15	-0.78	-0.42	-1.08	-1.21	-0.96
Wigton	SCOTLAND	-0.15	-0.68	-0.42	-0.54	-1.21	-0.43
ANGLESEY	WALES	-0.15	-0.78	-0.42	-0.30	0.38	-0.54
BRECKNOCKSHIRE	WALES	-0.15	-0.78	-0.42	-0.02	-0.05	-0.23
CARDIGANSHIRE	WALES	-0.15	-0.78	-0.42	-0.79	-0.51	-0.55
CARMARTHENSHIRE	WALES	-0.15	-0.78	-0.42	-0.63	0.24	-0.67
CARNARVONSHIRE	WALES	-0.15	-0.78	-0.42	-0.02	-1.21	-0.18
DENBIGHSHIRE	WALES	-0.15	-0.78	-0.42	-0.46	-0.15	-0.68
FLINTSHIRE	WALES	-0.15	-0.78	-0.42	-0.32	-1.21	-0.75
GLAMORGANSHIRE	WALES	-0.15	-0.78	-0.42	0.18	1.50	-0.17
MERIONETHSHIRE	WALES	-0.15	-0.78	-0.42	-0.74	-1.21	-0.68
MONMOUTHSHIRE	WALES	-0.15	-0.78	-0.42	-0.38	-0.05	-0.56
MONTGOMERYSHIRE	WALES	-0.15	-0.78	-0.42	-0.72	-0.77	-0.70
PEMBROKESHIRE	WALES	-0.15	-0.78	-0.42	-0.30	0.01	-0.11
RADNORSHIRE	WALES	-0.15	-0.78	-0.42	-0.95	-1.21	-0.94

Figure 2.16: Core KAIs per Capita versus Peripheral KAIs per Capita, 1851 (z-scores)



How did KAIs affect Economic Growth? A General Equilibrium Perspective

How did KAIs facilitate the British Industrial Revolution? To state the answer rigorously and to help guide empirical work later in the thesis, in this section I model the general equilibrium effect of KAIs on economic growth using an endogenous growth model that incorporates both Paul Romer and Joel Mokyr's views about the role of knowledge in economic growth (Romer 1990, Mokyr 2002). Then, using insights from management science and network theory I explore the day to day activities of KAIs.

Both Romer and Mokyr put knowledge at the heart of long-run economic growth. However, while Romer provides a formal explanation of how economic growth arises from the accumulation of new knowledge, Mokyr describes the fundamental discontinuity in the process of accumulating knowledge that occurred during the British Industrial Revolution. A joint approach is required to describe the general equilibrium effect of KAIs on the British Industrial Revolution.

In Romer's 1990 model, the growth of knowledge $\dot{A}_t$ is governed by the following equation:

$$\dot{A}_t = \delta A_t L_R$$

where L_R is labour engaged in the search for new knowledge, A_t is the existing knowledge stock at time t and δ is a parameter for the productivity of labour engaged in the search for new knowledge. The search for knowledge is motivated by profit, i.e. L_R is determined endogenously by the market for technological innovations, which are the fruits of the search for knowledge. The more labour engaged in the search for new knowledge and the greater the existing stock of knowledge, the faster new knowledge is found. Knowledge is a non-rival good, i.e. one person's use does not preclude another's, and excludable, i.e. at least part of its social return can be appropriated through mechanisms such as patenting or secrecy. For Romer, all productively useful knowledge has these characteristics, so if appropriation mechanisms are available and markets are large enough then the conditions for modern economic growth are satisfied.

In contrast, Mokyr sees an important distinction between two types of useful knowledge: *propositional* and *prescriptive* knowledge. Propositional knowledge, Ω_t, is knowledge about nature and its regularities, which includes but is not limited to scientific knowledge. Unlike Romer's unidimensional knowledge, it is typically non-excludable because it cannot usually be patented. Moreover, it is not typically produced for profit *per se* but rather by researchers operating within the institutional setting and norms of science, motivated by reputation-based returns. These alternative incentives tend to give rise to the open dissemination of knowledge as opposed to secrecy (David 2014). As such, the rate of growth of propositional knowledge is determined by the scale and efficacy of scientific institutions. During the British Industrial Revolution, this would have been determined by the size and efficacy of the KAI infrastructure.

Prescriptive knowledge, λ_t, on the other hand is the set of known techniques for manipulating the natural world, essentially the current stock of technology. It is largely excludable by patenting and its rate of growth is sensitive to prospective profits, in turn a function of market size and the efficacy of appropriation mechanisms.[27]

Propositional and prescriptive knowledge are economic complements. The larger the base of propositional knowledge, the higher the productivity of the search for new prescriptive knowledge. This is because a deeper understanding of underlying principles and regularities generally cuts the length of the path of trial and error. Hence, the accumulation of techniques is an increasing function of the size of the propositional knowledge base:

$$\dot{\lambda}_t = f(\Omega_t, .)$$

Conversely, the accumulation of the propositional knowledge base is itself a function of the state of the prescriptive knowledge base:

$$\dot{\Omega}_t = g(\lambda_t, .)$$

[27] Because prescriptive knowledge includes final goods alongside capital goods, it is not equivalent to the technology in Romer's model. Nevertheless, Romer's technology is a sub-component and serves as an adequate representation of prescriptive knowledge in a general equilibrium framework.

This is because technology such as observation instruments, measuring devices and computers help scientists discover new propositions.

Size is not the only parameter of the propositional knowledge base that influences the productivity of inventors. The user costs of the propositional knowledge base depend on its *density* and *tightness*. The density of propositional knowledge refers to how widely its elements are known across society. In the extreme cases, if each piece of propositional knowledge is held by only one individual then the propositional knowledge base has minimal density and if each element is held by every member of society then it has maximal density.[28] Higher density implies lower average knowledge access costs for individuals. The tightness of propositional knowledge refers to the degree of consensus held on the elements. Contradictory beliefs about the efficacy of a medical treatment, for example, lowers tightness. Whether tightness enhances inventor productivity depends on how propositional knowledge is verified and legitimised in society. Uniform belief in any proposition, no matter what it is, corresponds to maximal tightness. However, the adoption and acceptance of the scientific method, as upheld and promoted by appropriate institutions, produces a positive correlation between tightness and inventor productivity. Furthermore, under these conditions, scientific research makes knowledge tighter still over time. As described below, KAIs affected both the density and tightness of the propositional knowledge base during the British Industrial Revolution.

The Romer-Mokyr Model of the British Industrial Revolution

There are four main features of the model. First, as in Romer's model of 1990, technological innovation results in economic growth by raising productivity in the production of an homogenous final good, which households consume and from which they derive utility[29]. This final good is produced by firms under perfect competition, using labour and capital goods. However, rather than there being a single homogenous capital good as in the standard neoclassical framework, there are instead many different varieties. Productivity in the production of the final good is an increasing function of the variety of capital goods used, and

[28] While the size of society's propositional knowledge base is a function of the intersection of all individuals' knowledge, its density is a function of their union.

[29] The representative consumer's utility function is a standard constant relative risk aversion (CRRA) utility function of the form: $u(c) = \frac{c^{1-\varepsilon} - 1}{1-\varepsilon}$, where $\varepsilon > 0$ is a relative risk aversion measure. An important implication of this utility function is that the relationship between the real rate of interest and the growth rate of the economy obeys the Euler equation $r = \varepsilon g + \rho$ where ρ is the consumer's rate of time preference.

technological innovation is manifest by the creation of new varieties of capital goods. The economy's aggregate production function in period t is[30]:

$$Y_t = L_M^{1-\alpha} \int_0^{\lambda_t} x_i^{\alpha} \, di \qquad (3.1)$$

where the x_i's (where $i \in 0,\ldots,\lambda_t$) represent different varieties of capital good used in production in period t and α represents the degree of substitutability between them. Second, technological innovation is the result of innovative effort motivated by profit maximization. The fruit of innovative effort is the capital goods subset of Mokyr's prescriptive knowledge. A unit of prescriptive knowledge is a technological innovation in the form of a new capital good, x_i (i.e. $\dot{\lambda}_t > 0$). It is subsequently patented and sold to the final goods sector under monopoly conditions.

Third, technological innovation, or the growth of the stock of prescriptive knowledge/new capital goods, $\dot{\lambda}_t$, occurs according to the following equation, where L_R is labour allocated to innovative effort, Ω_t is the stock of propositional knowledge and δ is a productivity parameter.

$$\dot{\lambda}_t = \delta \Omega_t(\lambda_t) L_R$$

Ω_t contains all knowledge in existence at time t that might be useful for the invention of new capital goods. As such, the productivity of innovative effort is an increasing function of the existing stock of propositional knowledge, which in turn contains knowledge of the existing stock of technology. Hence, Ω_t is expressed as a function of λ_t.

Fourth, each unit of labour is allocated either to the production of the final good or technological innovation[31], so $L = L_M + L_R$. There is free entry to both activities, so in

[30] In Romer's model new capital goods do not render existing capital goods obsolete. Growth is achieved through increasing "product variety". However, obsolescence (or creative destruction) is inherent to technological change. It is captured in Aghion and Howitt's (1992) seminal "quality ladder" endogenous growth model, which offers an alternative approach to modelling endogenous growth to Romer (1990). Although creative destruction was exhibited during the British Industrial Revolution, incorporating it into the model presented in this chapter adds little to the analysis of the effect of KAIs on technological innovation, while adding complexity. I therefore base the analysis on Romer (1990).
[31] i.e. there is no demand for leisure.

equilibrium the return to each must be equal, meaning that wages are equal across the two activities: $w_M = w_R$.

Solving the model consists of finding the equilibrium split of labour allocated to manufacturing and innovative effort. This allocation determines the equilibrium growth rate of the economy. The starting point is the return flowing to innovative activity, which is equal to

$$\Pi_R = \frac{\Pi_C}{r}\,\delta\Omega_t(\lambda_t)L_R - \,w_t\,L_R$$

where Π_C is the earnings flow to each monopolist in the manufacture and sale of his/her respective variety of capital good to the final goods sector, not including fixed research costs. Because there is free entry into innovative activity this return must be zero in equilibrium, hence:

$$r = \delta\Omega_t(\lambda_t)\frac{\Pi}{w_t} \qquad (R)$$

This is the research arbitrage equation common to many endogenous growth models, which determines the relative allocation of labour to research and manufacturing. To make use of it one needs to find the equilibrium wage rate, w_t, which is equal to the marginal product of labour in the production of the final good. Since the economy's production function is:

$$Y_t = L_M^{1-\alpha}\lambda_t x^\alpha$$

the marginal product of labour equals

$$w_t = \frac{\partial Y_t}{\partial L_R} = (1-\alpha)L_M^{-\alpha}\lambda_t x^\alpha \qquad (3.2)$$

Next, one calculates the capital goods monopolist's choice of x, which is chosen by maximizing profits subject to the inverse demand curve of the final goods sector. This is equal to the marginal product of the capital good in the final sector, which is

$$p = \alpha L_M^{1-\alpha} x^{\alpha-1}$$

Hence, each capital goods monopolist maximizes

$$\Pi_C = \max_x\{px - x\} = \max_x\{\alpha L_M^{1-\alpha} x^{\alpha-1}\}$$

which implies the profit maximizing output (i.e. differentiating with respect to x and setting this derivative to zero):

$$x = L_M \alpha^{\frac{2}{1-\alpha}} \quad (3.3)$$

As such, (3.2) can be written as

$$w_t = (1-\alpha)\alpha^{\frac{2\alpha}{1-\alpha}}\lambda_t \qquad (3.4)$$

Furthermore, (3.3) implies that the equilibrium flow to monopoly production and sales of the capital good, Π_C, equals

$$\Pi_C = L_M \alpha^{\frac{2}{1-\alpha}} \qquad (3.5)$$

The research arbitrage equation, R, can now be re-written using (3.4) and (3.5) as

$$r = \alpha \frac{\delta\Omega_t(\lambda_t)}{\lambda_t} L_M \quad (3.6)$$

This can be re-arranged and, using the assumption stated above that $L = L_M + L_R$, re-written with L_R on the left hand side:

$$L_R = L - \frac{r\lambda_t}{\alpha\delta\Omega_t(\lambda_t)}$$

Since the growth rate of the economy, g, is proportional to the growth rate of product variety, we have

$$g = \frac{1}{\lambda_t}\dot{\lambda_t} = \frac{\delta\,\Omega_t(\lambda_t)}{\lambda_t} L_R$$

Substituting in (3.6) for research labour and the Euler equation in footnote 29 for r gives

$$g \; = \frac{\alpha \dfrac{\delta\,\Omega_t(\lambda_t)}{\lambda_t} L - \rho}{\alpha + \varepsilon}$$

This equation is similar to Romer's growth equation (Romer 1990). Growth is proportional to population[32] and the productivity of R&D and inversely proportional to the rate of time preference and the substitutability between capital goods innovations. The key difference between the growth equation presented here and that of Romer's is that it features the size of the propositional knowledge base. Moreover, this knowledge base is a function of exogenous institutional factors (including their effect on density and tightness). Furthermore, the rate of growth of the propositional knowledge stock is a function of the state of technology, so a change in institutions affects the rate of technological innovation directly in the first instance and then further via positive feedback effects over time as new technology facilitates the search for new knowledge. As Mokyr argues, these feedback dynamics may have been important to the establishment of sustained modern economic growth (Mokyr 2002).

The growth equation above helps illustrate the mechanism through which KAIs affected the rate of technological innovation and economic growth. KAIs raised the rate of technological innovation and economic growth *directly* by raising the productivity of R&D labour and then *indirectly* by raising the share of labour allocated towards R&D in equilibrium (by raising the relative marginal productivity of R&D labour compared with manufacturing labour as captured in equation *R*). As explained below, KAIs achieved this by making two contributions to the R&D process. First, KAIs promoted and facilitated a culture of *scientific R&D* – the application of the scientific method and scientific norms to the practice of industrial R&D – which led to

[32] human capital adjusted-population in Romer (1990)

a faster exogenous growth rate of the propositional knowledge base. Second, they reduced the cost of access to the existing propositional knowledge base for inventors and entrepreneurs.

One can illustrate the general equilibrium effect of reducing the cost of access to the propositional knowledge base by extending the Romer-Mokyr model to incorporate multiple regions, following, in spirit, Rivera-Batiz and Romer (1991)[33]. To take the most basic case, assume that there are now two regions in the British economy, in each of which prospective innovators have access to their own regional propositional knowledge base, but not the propositional knowledge base of the other region.[34] For simplicity, assume also that these two knowledge bases are perfect complements, i.e. they possess no propositional knowledge in common and are the same size. The introduction of a system of KAIs in this economy – i.e. at least one KAI in each region, which communicate with one another – lowers the cost of access for each region to the other region's propositional knowledge base. This raises the steady state rate of economic growth.

First, note that before the introduction of KAIs, although the two regions do not share propositional knowledge, they are integrated by a common market for capital and consumer goods (as were British regions on the eve of the Industrial Revolution). What is the growth rate of this trade-integrated, knowledge-autarkic economy? Trade in capital goods between the two regions means that the marginal product of manufacturing labour in each region is twice as high as it would be under trade autarky, rising from $(1-\alpha)L_M^{-\alpha}\lambda_t x^\alpha$ to $(1-\alpha)L_M^{-\alpha}(\lambda_t + \lambda_t')x^\alpha$, where λ' represents the prescriptive knowledge base of the other region. But the market for new capital goods doubles due to trade too, so the marginal productivity of research labour also doubles, from δP_λ to $2\delta P_\lambda$. The overall effect is that the share of labour allocated to research in each region is unchanged. Long run growth with inter-regional trade is no faster than without it.

In contrast to trade between regions, the integration of knowledge bases through KAIs does effect relative labour productivities. The productivity of labour in research doubles to:

[33] who consider the Romer model in a multiple-country setting.

[34] i.e. there is a fundamental impairment of density due to a step function across space in communication costs indeed communication costs across regions are infinitely large.

$$\dot{\lambda}_t = \delta 2\Omega_t(\lambda_t)L_R \qquad (3.7)$$

This has two effects on the economy's equilibrium growth rate. First, the increase in the productivity of research directly increases the rate of technological innovation. Second, the rise in research productivity relative to manufacturing productivity raises the equilibrium labour allocation to research. Equilibrium research labour is now

$$L_R = L - \frac{r\lambda_t}{\alpha\delta 2\Omega_t(\lambda_t)}$$

And the equilibrium growth rate is now

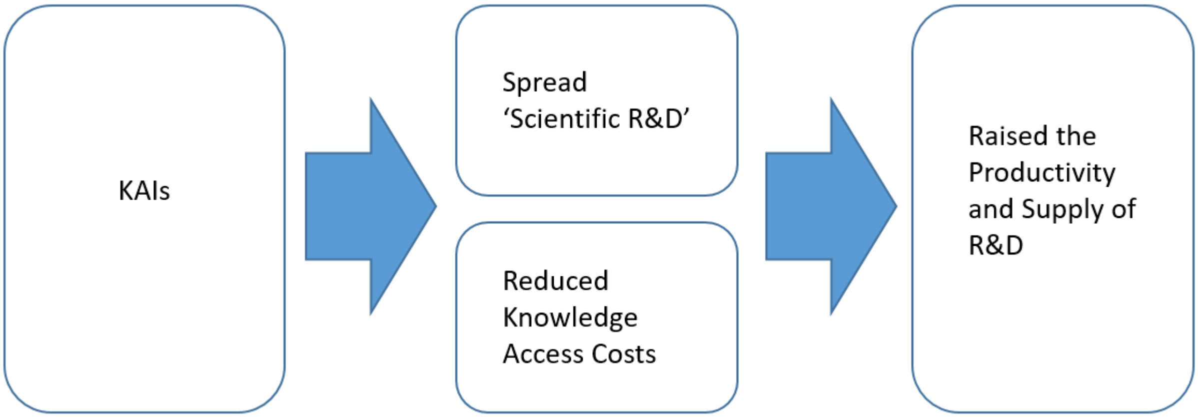
$$g = \frac{\alpha \frac{\delta\, 2\Omega_t(\lambda_t)}{\lambda_t} L - \rho}{\alpha + \varepsilon}$$

Hence, the reduction in knowledge access costs achieved by KAIs raises the steady-state rate of economic growth.

Inside the 'Black Box' of KAIs: 'Scientific R&D' and Network Effects

Figure 2.17 summarises the effect of KAIs on economic growth. KAIs raised the productivity and equilibrium supply of British industrial R&D by promoting a culture of 'scientific R&D' in British industry and reducing propositional knowledge access costs for British industrialists. Scientific R&D can be considered the application of the scientific method and the worldview and norms of science, established during the Scientific Revolution, to the industrial R&D process. Its adoption within British industry during the eighteenth century amounted to a broad behavioural change towards innovation, and KAIs helped to establish this new behaviour as a part of British culture (Musson & Robinson 1968, Inkster 1997, Jacob 1997, 2014, Jacob & Stewart 2004, Mokyr 2002, 2005, 2009, Goldstone, 2002, Elliott 2003). Regarding the second channel, KAIs helped to reduce knowledge access costs by strengthening and extending social, correspondence and publication networks within the scientific, technological and industrial community. Furthermore, the two channels were mutually reinforcing. Scientific norms encouraged communication and the sharing of knowledge while, in turn, greater social connectivity facilitated the cultural diffusion of the practice of scientific R&D.

Figure 2.17: KAIs and Economic Growth



KAIs and Scientific R&D

KAIs helped to raise the growth rate of the propositional knowledge stock by absorbing, cultivating and spreading throughout British industry what Margaret C. Jacob calls a 'scientific culture' and what Joel Mokyr calls the 'Industrial Enlightenment' (Jacob 1997, 2014, Mokyr 2002, 2005)[35]. Whether the high scientific theory of the sixteenth and seventeenth century Scientific Revolution – of Copernicus, Galileo, Kepler, Descartes, Huygens and Newton – was directly instrumental to the British Industrial Revolution or not has been vigorously debated, but is beside the main point.[36] What really mattered was the application of the *ethos* of the Scientific Revolution to industrial R&D in eighteenth century Britain (Musson & Robinson 1968, Jacob 1997, 2014, Goldstone, 2002, Mokyr 2002, 2005). As the eighteenth century progressed, the experimental scientific method employed in the pursuit of "the relief of man's estate" as envisaged by Francis Bacon in the 1620s and later exemplified by Robert Boyle and Newton characterised the behaviour of a growing number of British industrialists seeking to

[35] While Mokyr sees the Industrial Enlightenment as a Western European phenomenon in which Britain held no discernible pre-eminence, Jacob sees British scientific culture as advanced relative to the rest of Western Europe.

[36] The classic study linking science and the Industrial Revolution is Musson & Robinson (1969) and refutations: Hall (1974), Mckendrik (1973), Gillespie (1980), Mathias (1979). For recent expositions on opposing sides of the debate see O'Grada (2014) and Wootton (2016).

profit from success in R&D projects concerning problems of industrial production across the economy. As Josiah Wedgwood put it to a friend in 1766: “Many of my experiments turn out to my wishes, and convince me more and more, of the extensive capability of our Manufacture for further improvement...Such a revolution, I believe, is at hand, and you must assist in, [and] profit by it” (Wedgwood 1903). Moreover, the growing belief in nature’s predictability and manipulability, especially following Newton’s articulation of the mechanical laws of nature and the popular dissemination of the Newtonian worldview during the early eighteenth century by famous Newtonians such as John Theophilus Desaguliers made costly and painstaking R&D projects appear worth a shot (Jacob and Stewart 2004). The body of ‘modern’ scientific knowledge accumulated during and following the Scientific Revolution – in the fields of astronomy, mechanics, chemistry, optics, electricity, hydrostatics, magnetism, pneumatics, among others – often supplemented by an exposition of practical industrial applications, formed the basis of a common mathematical, scientific and technical education among a slice of British industrialists, endowing them with, alongside a stock of advanced human capital, a common technical language within industrial R&D.[37] Furthermore, scientific experimental protocol and rising standards of measurement precision, critical for the technological achievements of the Industrial Revolution, bled from high science into industrial R&D projects (Heilbron 1990).

All of this was fundamental to the British Industrial Revolution because the technological innovation that characterised the era was contingent upon unprecedented levels of R&D effort and sophistication (Allen 2009). Within the development of steam power, the seventeenth century scientific insights of Galileo, Evangelista Torricelli, Otto von Guericke, Huygens and Boyle provided the inspiration for the first commercial application of steam technology in the form of pumps to drain mines, attempted unsuccessfully in the first instance by Thomas Savery in 1698 and then successfully by Thomas Newcomen in 1712. But in terms of perspiration, Newcomen undertook a decade long R&D programme – notably, twentieth century engineers recreating Newcomen engines have found it difficult to make them work (Hills 1989, Allen 2009). James Watt spent the early 1760s working on Newcomen engines at the University of Glasgow, experimenting on and calculating the amount of energy required to

[37] This education was often obtained outside of the English university system, either at the cheaper, less restrictive and more scientifically progressive Scottish universities (Clow & Clow 1952), the English dissenting academies (Elliott 2010), or often informally through itinerant lecturers extensively touring London and the provinces during the eighteenth century, and the growing scientific and technical literature (Musson & Robinson 1968).

change gas to liquid. He then spent the late 1760s and almost £1,000 of venture capital funds experimenting on model engines and a prototype of his famous engine with separate condenser (Hills 1989, Allen 2009). On account of his rigorous R&D projects, Watt saw himself as a 'man of science' and consistently referred in his correspondences to his scientific method. He copied out experiments by Priestly and La Place in his notebooks alongside his own experiments on heat and his engines (Jacob 2014). Wedgwood too sought to apply the scientific method rigorously to industrial R&D, as evidenced by his famous '5,000 experiments' on clay mixtures and glazes. In establishing his manufactory's famous experimental approach employed chemical lecturer William Lewis' technician Alexander Chisolm (Stewart 2008). In water power, John Smeaton experimented extensively on model water wheels in ascertaining the superior efficiency of the overshot breast water wheel to the undershot water wheel (Allen 2009). Although Joseph Black, Professor of Chemistry at Glasgow and Edinburgh Universities described Henry Cort, the inventor of the important iron puddling and rolling process (1784), as a "plain Englishman, without Science", he did concede that his discovery was due to "a dint of natural ingenuity and a turn for experiment". Moreover, the fact that Cort took the trouble to consult Black for scientific advice tells us that Cort, although perhaps an outsider to scientific culture, was clearly operating under it influence (Mokyr 2009).

Likewise, the fact that innovation within the textile sector – which contributed more than any other sector of the British economy to labour productivity growth during the Industrial Revolution (Clark 2007) – owed nothing directly to scientific knowledge did not mean that the culture of scientific R&D played any less a role. James Hargreaves, Richard Arkwright, Samuel Crompton, Edmund Cartwright and Richard Roberts all embarked on painstaking and costly R&D projects to crack difficult problems within the replication of human dexterity by powered machines (Allen 2009). Chlorine bleaching was an important invention in the finishing of textiles and one of the most important chemical inventions of the early Industrial Revolution. The basic scientific breakthrough was made in continental Europe: chlorine was discovered Carl Willhelm Scheele, a Swedish chemist, in 1774 and its bleaching properties discovered by Claude Berthollet, one of the leading students of Lavoisier. However, many years of R&D were undertaken by British industrialists, including Watt's father in law and Boulton, until in 1799 Scottish bleacher Charles Tennant combined chlorine with slaked lime to produce a commercially successful bleaching powder (Clow & Clow 1952).

A shared scientific culture was essential for the application of steam power to textiles. Early adopters of steam within textile production, such as James M'Connel and John Kennedy of Manchester needed to be conversant in the language of scientific culture to collaborate with Watt and Boulton on the installation and adaptation of Watt's engine to the context of the cotton mill (Jacob 2014). Likewise, Benjamin Gott relied upon scientific cultural acumen in transferring cotton textile innovations to the wool industry in Leeds (Jacob 2014). These are extremely important examples of the principle of 'absorptive capacity', essential for the realisation of much of the potential productivity gains from invention (Cohen & Levinthal 1990).

By providing an institutional basis for the eighteenth century British scientific-industrial community in the form of the metropolitan elite and provincial learned societies, and by extending the franchise via mechanics' institutes in the early nineteenth century, core KAIs absorbed and greatly strengthened British scientific culture. They encouraged and spread the behaviours that constituted this culture, raising the supply and productivity of industrial R&D projects, exemplified by the famous cases listed above and thousands more besides. Core KAIs put individuals searching for prescriptive knowledge under the same roof as purveyors of propositional knowledge, which meant that the scientific methodology and norms of experimentation, accurate measurement, mathematical representation, dispassionate reporting of results and publication of results became established practice in British industrial R&D. Consider figure 2.18, which is a chronological list of papers read at the Royal Philosophical Society of Glasgow in 1841 and 1842. Drawing a distinction between propositional and prescriptive knowledge is a somewhat subjective procedure, however, of the 53 papers listed here, 37 appear to be oriented towards an exposition of propositional knowledge and 16 towards prescriptive knowledge. Each paper was read at the same regular seminar to the same returning audience. Figure 3.19 extracts two adjacent papers, the second and third on the programme: *"On the determination of the melting points of metals and various metallurgic products and on the temperature required for the formation of different silicates*" and "*On the means of extinguishing fires in factories".* The first is an archetypical exposition of propositional knowledge: some equations and calculations followed by a systematic tabulation of the empirical properties of various chemical elements. The second begins by stating a pressing local practical problem: "The extensive fires that have lately occurred in two of the largest factories in this city have had their origins in the upper floors of buildings". It then provides a detailed description, with a careful illustration, of a proposed fire extinguishing system in the form of a device that is added on to the building's existing cistern. This is the process of the accumulation and dissemination of prescriptive knowledge, as shaped by the Scientific Revolution – the culture of scientific R&D. In the early nineteenth century, mechanics institutes taught science to mechanical operatives, who possibly gained more by absorbing scientific culture than the scientific knowledge imparted to them, which cannot always have been easy to take in during the evening after a day's work.

Partha Dasgupta and Paul David (1994) argue for the general influence of scientific norms on industrial R&D. Two norms that they emphasise that stand out in the case of KAIs during the British Industrial Revolution are publication and reputation-based reward. Scientific publication switched from books to journals during the British Industrial Revolution, as figure 2.20 illustrates using data from Allen, Qin and Lancaster (1994). In 1700, over 80% of citations in the *Philosophical Transactions* of the Royal Society were of books and only around of 10% journal articles. By 1850, this had shifted substantially to a 50% share each. Latin publications almost disappeared between 1700 and 1850, from 60% of publications cited by the Philosophical Transactions to less than 10%, as chart 2.21 shows. Core KAIs, including those focused more on R&D than science embraced the periodicals revolution. Scudder (1879) of Harvard University Library counts 568 British institutions that had published a scientific or technological periodical by 1876. Olav Sorenson and Lee Fleming (2004) have shown using patent citation data linked to scientific publication citation data, the beneficial impact of scientific publication on the rate of technological innovation via the enhanced dissemination of knowledge. Robert Allen (1983) and Alessandro Nuvolari (2004) have emphasised the role of collective invention – the sharing of R&D results among industrial competitors – during the British Industrial Revolution.

Individuals were incentivised to allocate effort to R&D by status-oriented reward mechanisms borrowed from science, such as titles and prizes (Dasgupta and David 1994). Titles and prizes bestowed social status upon individual recipients but, importantly, also raised the profile and social status of 'the inventor' in general. Both the Royal Society and the Society for the Encouragement of Arts offered meaningful status-based incentives for industrial R&D.

Figure 2.18: Papers read at the Royal Philosophical Society of Glasgow, 1841-4

(Proceedings of the Royal Philosophical Society of Glasgow Volume 1, 1842)

CONTENTS.

Figure 2.18: continued.

iv CONTENTS.

Figure 2.19: Two consecutive papers read at the Royal Phil Soc of Glasgow 1841

1st December, 1841,—*The* PRESIDENT *in the Chair.*

THE following gentlemen were admitted members:—William Ramsay, Esq., James F. Stewart, Esq., R. D. Thomson, M.D., James Thomson, Esq., Jun., Thomas Stenhouse, Esq., William More, Esq.

The following communication was then read:—

II.—*On the Determination of the Melting Points of Metals and various Metallurgic Products, and of the Temperature required for the formation of different Silicates. By* LEWIS D. B. GORDON, Esq., *Regius Professor of Civil Engineering and Mechanics, University of Glasgow.*

IN reviewing the state of our knowledge of the melting points of bodies, seven different classes of pyrometers that have been employed or proposed by experimenters were briefly mentioned, and it appeared that the many researches undertaken by philosophers with those instruments afford us only a *graduated scale of the fusibility* of the substances tried, and do not give *the absolute melting* points, save for a certain number of metals in their simple state.

Table No. I. gives the results of different experimenters, from which it appears how little, on the whole, had been done in this important subject until Plattner of Freyberg undertook a most elaborate series of experiments, of which, and of their results, it is the object of this paper to give some account.

Plattner was guided in his course of research by the methods of Prinsep and Daniell, but more especially by the method of de Saussure, for determining the melting points.

Saussure's method consisted in endeavouring to determine the fusing point of a substance in degrees of Wedgewood's pyrometer, according to the diameter of the greatest assay he could fuse before the blowpipe, by comparison with the diameter of the greatest globule of silver he could melt under circumstances in every respect the same, and the melting point of which he knew.

[The instruments employed, and method of experimenting adopted by Plattner for perfecting this notion of de Saussure, were exhibited and explained.]

For determining the melting points of the more easily fusible products, alloys of gold and silver, and silver and lead, (see Table II.) were employed; and for those of the more refractory products, alloys of *gold and platinum* were used.

The determination of the melting point of *platinum* was a preliminary step, and this was ascertained by two experiments, as follows:—

1°. It was found that with a blowpipe supplied with air, under a gentle pressure, from a gasometer, a gold regulus weighing 2290 *milligrammes*, can be fused and maintained in fusion on charcoal, and

in the same circumstances, an alloy of 1760 mill. gold + 230 mill. platinum can be maintained in fusion; and if either more gold, or a very small quantity of platinum, be added, the fusion is imperfect.

2°. An alloy of gold and platinum was found having the same melting point as *cast iron*, viz., 70 gold + 30 platinum fused in the same time as 100, by weight, of cast iron.

The melting point of platinum is deduced from these experiments to be—

$$\text{From } \left.\begin{matrix} 1^{\circ}\ 2529^{\circ}\text{ C.} \\ 2^{\circ}\ 2539^{\circ}\text{ C.} \end{matrix}\right\} \text{Mean, } 2534^{\circ}\text{ C.}$$

and these experiments appeared satisfactorily to warrant the assumption that *alloys of silver and gold,* and *gold and platinum, have melting points proportional to the melting points of each of these metals;* an assumption made by Prinsep.

Mitscherlich's determination of 1560° C. as the melting point of platinum was referred to, but as this involves all previous determinations of the melting points of other metals being erroneous, that is, much too high, Plattner was justified in assuming his own determination as the basis of the temperatures given in Table II. and in his further researches.

The melting points of Lead being taken at 334° C.
Silver, — 1023° C.
Gold, — 1102° C.
Platinum, — 2534° C.

it was easy, according to the method described, to determine the melting points of the most refractory substances, so long as these were under that of platinum. The alloy being found having the same melting point as that of the body under research, its value was then

$$x = \frac{A\,s + B\,s'}{100}$$

Where A and B are the weights, and s and s' the melting points of the metals contained in the alloys. And 100 parts by weight of alloy, and body under experiment, were taken respectively.

Attention was called to the circumstance that Daniell had fixed the melting point of copper at 1091° C., or under that of gold. Prinsep found, from constant experience as an assayer, that this is not the case, and fixed the melting point to be the same as that of an alloy of 97 parts gold and 3 parts platinum. Plattner found 95 parts gold and 5 platinum to answer more exactly, and hence, applying the above formula,

$$x = \frac{95 \times 1102^{\circ} + 5 \times 2534^{\circ}}{100} = 1173^{\circ}$$

the melting point of copper.

The second part of Plattner's researches *on the Determination of the*

Temperature necessary for the Formation of different Silicates, was promised, should the society consider it of sufficient interest, as the subject of a future communication.

TABLE I.

TABULAR VIEW OF THE MELTING POINTS OF METALS, AS DETERMINED BY DIFFERENT EXPERIMENTERS.

Tin melts at	228°	Centigrade, according to	Crichton.
Do. do.	267°	....	Guyton.
Do. do.	228°	....	Rudberg.
Do. do.	230°	....	Kupffer.
Do. do.	222·5°	....	Ehrmann.
Bismuth do.	246°	....	Crichton.
Do. do.	241°	....	Guyton.
Do. do.	265°	....	Rudberg.
Do. do.	264°	....	Ehrmann.
Lead do.	322¼°	....	Crichton.
Do. do.	322·2°	....	Guyton.
Do. do.	325°	....	Rudberg.
Do. do.	334°	....	Kupffer.
Quicksilver boils at	350°	Centigrade, according to	Dulong and Petit.
Zinc hardens above	400°	....	Rudberg.
Do. melts at	411°	....	Daniell, measured with an *Iron Rod.*
Antimony do.	512°	....	Guyton.
Silver melts at	1023°	....	Daniell, measured with *Iron Rod.*
Do. do.	1034°	....	Guyton.
Do. do.	999°	....	Prinsep.
9 parts silver 1 part gold do.	1048°	....	do.
3 do. 1 do. do.	1121°	....	do.
Copper 1132° C. corrected to	1091°	....	Daniell, with Platinum rod.
Do. melts at	1207°	....	Guyton.
Do. do.	1173°	....	Plattner.
Gold, 1144° corrected to .	1102°	....	Daniell.
Do. melts at	1163°	....	Do. with *Iron Rod.*
Do. do.	1380°	....	Guyton.
Cast Iron, 1587° corrected to	1530°	....	Daniell, with Platinum rod.
Platinum melts at	2534°	....	Plattner.

TABLE II.

MELTING POINTS OF VARIOUS METALLURGIC PRODUCTS.

Name of the substance, the melting point of which is determined.	100 by weight of this substance melt in the same temperature and in the same time to a globule as alloys of	Melting point, deduced by calculation.
1. Sulphuretted metals, from process termed *Roharbeit*, ...	30 Gold, + 70 Silver,	= 1047°C.
2. Do. Lead process, ...	5 — + 95 —	= 1027°
3. Do. Copper do., ...	3 Lead, + 97 —	= 1002°
4. Arseniuretted Metals,—Lead, ...	50 Gold, + 50 —	= 1062°
5. Raw Copper, ...	5 — + 95 —	= 1027°
6. Red Litharge, ...	90 Silver, + 10 Lead,	= 954°
7. Slags:—		
a. Greenish yellow colour, and slight glass vitreous lustre, ...	84 Gold, + 16 Platinum,	= 1331°

Figure 2.19: continued.

TABLE II.—MELTING POINTS OF VARIOUS METALLURGIC PRODUCTS, *Continued.*

Name of the substance, the melting point of which is determined.	100 by weight of this substance melt in the same temperature and in the same time to a globule as alloys of					Melting point deduced by calculation.
b. Dark grey, slight vitreous lustre, . .	82	—	+ 18	—	=	1360°
c. Light grey colour, slight vitreous lustre, (Hot blast,)	83	—	+ 17	—	=	1345°
d. Dark grey vitreous lustre, slight, (Hot blast,)	82	—	+ 18	—	=	1360°
e. Dark grey, vitreous lustre, ...	83	—	+ 17	—	=	1345°
f. Grey and blue striped, and vitreous fracture, ...	84	—	+ 16	—	=	1331°
g. Dark grey, slight vitreous lustre, . .	83	—	+ 17	—	=	1345°
h. Same, Hot blast, ...	83	—	+ 17	—	=	1345°
Copper Slags, Raw Metal, ...	83	—	+ 17	—	=	1345°
Tin Slags, Pure, ... Block, vitreous lustre, ...	85	—	+ 15	—	=	1317°
Iron Slag, Blast furnace, going on No. 4 Iron, Slags, greenish coloured vitreous fracture,	80	—	+ 20	—	=	1388°
Iron Slag, Puddling, Iron, black colour, metallic lustre, slight, .	77	—	+ 23	—	=	1431°

15*th December*, 1841,—*The* PRESIDENT *in the Chair.*

THE following members were admitted:—Thomas Lindsay, Esq., William Lowe, Esq., J. G. Fleming, M.D., John Clugston, Esq., George Rich, Esq.

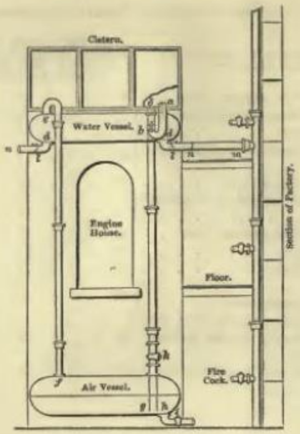
The following communications were read:—

III. *On the Means of Extinguishing Fires in Factories.*
By D. MACKAIN, M.I.C.E.

THE extensive fires that have lately occurred in two of the largest factories in this city have had their origin in the upper floors of the buildings. In one case, the fire began while the people were at work, and when the command of a very small quantity of water would have been sufficient to have extinguished it. In the other case, the fire began at night.

As the greater number of factories have cisterns of considerable capacity placed above the engine house, and at a height of about thirty feet from the ground, they could easily, and at a small cost provide themselves with the means of extinguishing fire in any part of their buildings, by adopting a modification of the apparatus most commonly known by the name of the Chemnitz, or Hungarian Machine. A sketch of the proposed mode of applying this apparatus is here given.

Below the cistern of the engine house, let there be placed an upper receiver, or, as it is termed in the sketch, *a water vessel*, formed of boiler plates. A pipe, *a*, *b*, having a curved end fitted with a valve, *b*, communicates between the cistern and the water vessel.



From the bottom of the water vessel, conduit-pipes may be carried and connected with others leading into the second floors of the factory below, and above the water vessel, to a height nearly equal to the distance between the water vessel and the air vessel yet to be described; and from these pipes, others fitted with fire-cocks may ramify through the entire extent of the buildings.

Nearly on a level with the ground is placed another receiver, marked in the sketch as the *air vessel*, and formed of the same materials as the water vessel, but of double its capacity. A pipe, *ƌ*, *g*, fitted with a stop-cock, *k*, leads from the bottom of the cistern to nearly the bottom of the air vessel.

Another pipe, *h*, also fitted with a stop-cock, *i*, is attached to the bottom of the air-vessel, for emptying it, after it has been filled with water. An air-pipe, *f*, *e*, is conducted from the top of the air-vessel, to the top of the water vessel, to which it descends with a curve, after having been carried to the height of the top of the cistern.

The apparatus being thus arranged, the presence of water in the cistern will raise the valve, *b*, on the curved pipe of the water vessel, and flow into it; and the lower cock, *i*, of the air vessel being opened, the air contained in the water vessel will be discharged by the air pipe, and the vessel will be entirely filled with water. If the cock, *i*, be shut, and the cock, *k*, be opened, the water will flow from the cistern into the air vessel, compressing the air in it, and in the air pipe, *f*, *e*, with the force due to the height of the column of water in the pipe. The compressed air will thus act, through the air pipe, on the

surface of the water in the water vessel, and the valve, *b*, being thereby shut, the water will be forced along the pipes, *m*, *n*, to the same height above the water vessel, as the distance between the surfaces of water in the cistern and air vessel.

Thus, if the air vessel be at the level of the ground,—the surface of water in the cistern be 30 feet above it,—and the water in the water vessel, 25 feet above the ground,—water will flow from the conduit-pipes at the height of 55 feet above the ground; and the pipes might be made to discharge any required volume, in a given time, below this point, by a proper adjustment of the diameters of the pipes, and of the difference between the several water surfaces. The velocity of discharge *below* the cistern, is that due to the extreme height to which the compressed air can raise the water in the upright pipe.

When the upper vessel is exhausted, the stop-cock, *k*, on the pipes leading from the cistern, is to be shut; the stop-cock, *i*, for discharging water from the air vessel, is to be opened; and the pressure being now taken off the water vessel, the valve, *b*, on the feeding pipe, will be opened by the water in the cistern; the water vessel will be charged, and the apparatus be again ready for use.

I understand that this machine is so arranged in Hungary that it is self-acting. It, therefore, would only require a stop-cock on the conduit-pipes, to be opened or to draw water in the event of fire, to set it in motion,—an instantaneous aid that, in such cases, is invaluable.

The greater size of the lower vessel is necessary to admit of the compression of the air to the requisite extent, and at the same time that there shall remain a bulk of compressed air equal to the contents of the water vessel, so as to expel the volume of water with which it was filled.

As air compresses into one half of its bulk, with a weight equal to that of the atmosphere, or of a column of water 33 feet in height, it follows, that by this apparatus only one half of the quantity of water which falls from the cistern into the lower air vessel, can be raised to the height of 33 feet above the water vessel, or 66 feet above the ground; and following out the law of compression, only one fourth of the quantity could be raised to 99 feet above it, or to 130 feet above the ground.

These are heights not usually coming within the scope of ordinary cases, in the circumstances now in view; but the pressures due to these heights can be produced by multiplying the number of cylinders on the same levels, and thus forces of great intensity, though of moderate ranges of extent, could be obtained by this apparatus, and rendered available for many purposes connected with manufactures and the arts.

(MR. MACKAIN exhibited a model of this apparatus, in which the receivers were 4½ feet apart, and a flow of water was produced from pipes connected with the water vessel, at the same height. A second pair of receivers were connected; and the pressure, amounting to double of the first pair, was exhibited by a column of mercury.)

Figure 2.20: Royal Society Article Citations by Books, Journals and Other

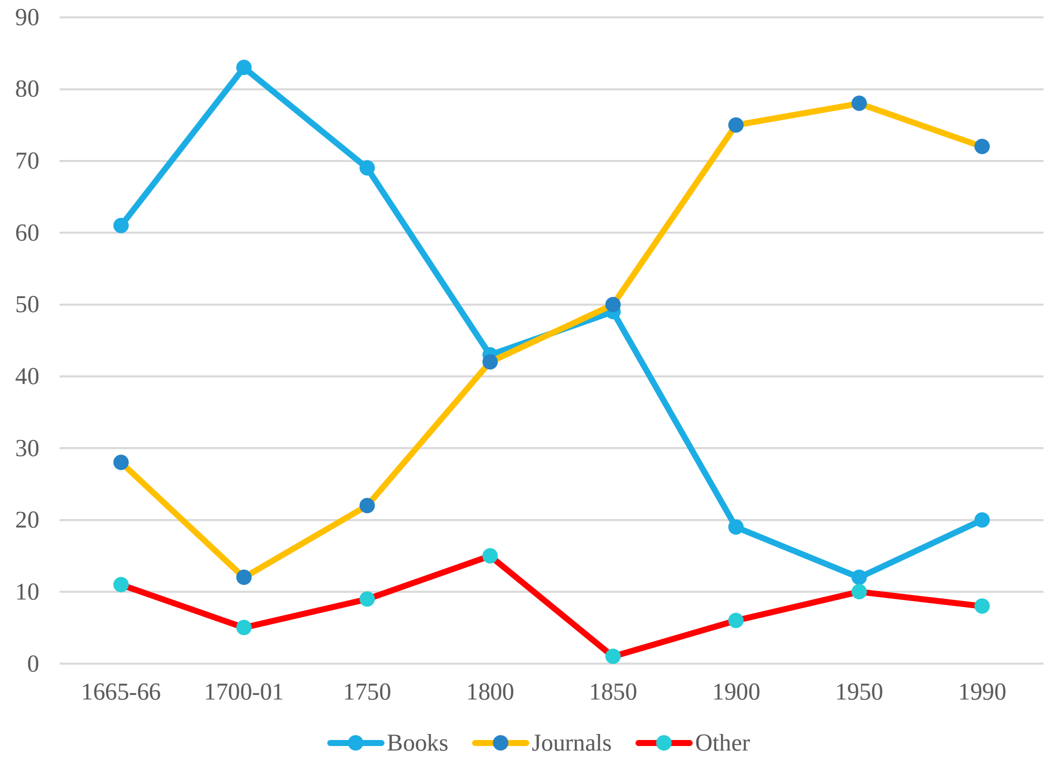
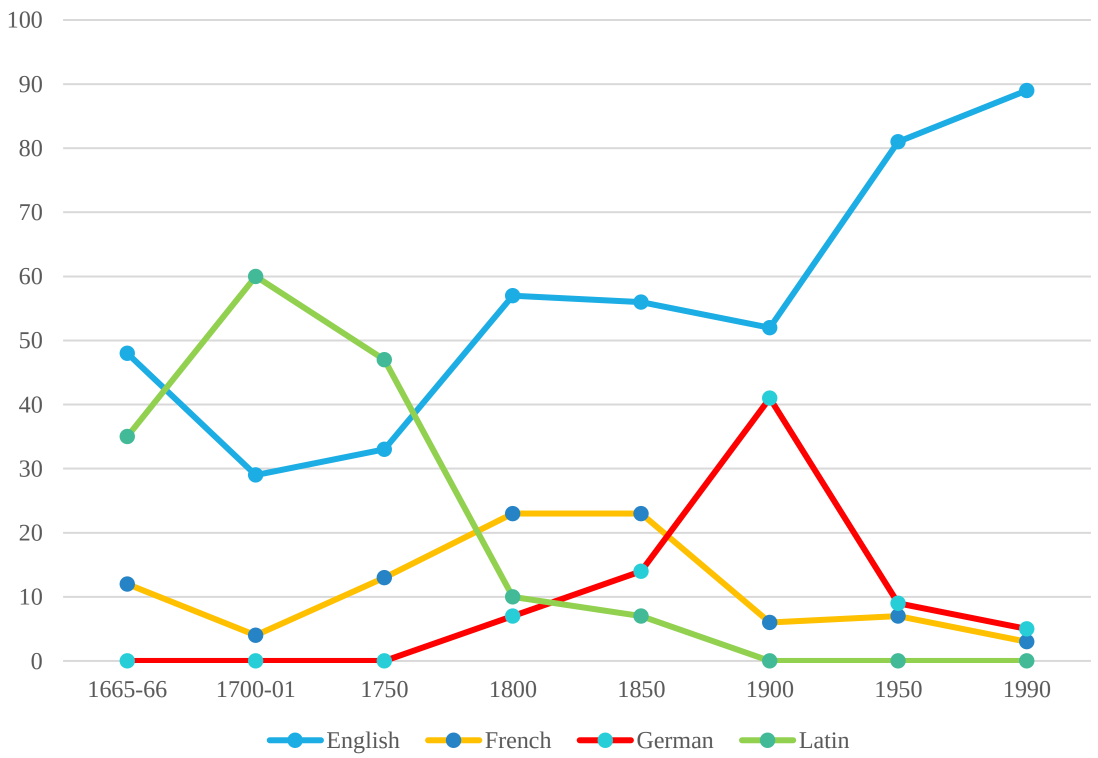


Figure 2.21: Royal Society Article Citations by Language



The Royal Society's Fellowships (*FRSs*) were highly prestigious and often awarded for applied work. O'Grada (2014) has questioned the relevance of the Royal Society Fellowships because some well-known individuals were awarded fellowships late in life, long after they had made their major scientific or technological contributions. But this was not generally the case as figure 3.23 shows. During the eighteenth century, the average age of an *FRS* at election was mid to late-30s and remained under 45 until 1850. By comparison, Anton Howes (2016) calculates from a new database of inventors during the British Industrial Revolution that the average age of inventors at the time of their important invention was 33. The Society for the Encouragement of Arts was also engaged in status-oriented reward mechanisms. Indeed, as table 2.6 shows, between its founding in 1754 and 1776, it spent more on medals for inventors (£24,616) than cash premiums for inventors (£23,552). Khan (2016) shows that there was no detectable direct link at the sectoral level between the society's awards and innovation rates. However, the society's most important contribution to innovation was to promote and bestow prestige upon inventing in general. As a nationally visible institution patronised by London's social, intellectual and commercial elites, it punched above its weight in doing so. Regarding the direct effects of prizes in the nineteenth century, Brunt, Lerner and Nicholas (2012) show at the level of individual innovations a positive effect on agricultural innovation of monetary prizes and medals awarded by the Royal Agricultural Society of England from 1839 onwards, finding a larger effect for medals than monetary awards.

Figure 2.22: Royal Society Fellowships, Average Age at Election and Death, 1660-2013 (10y moving average)

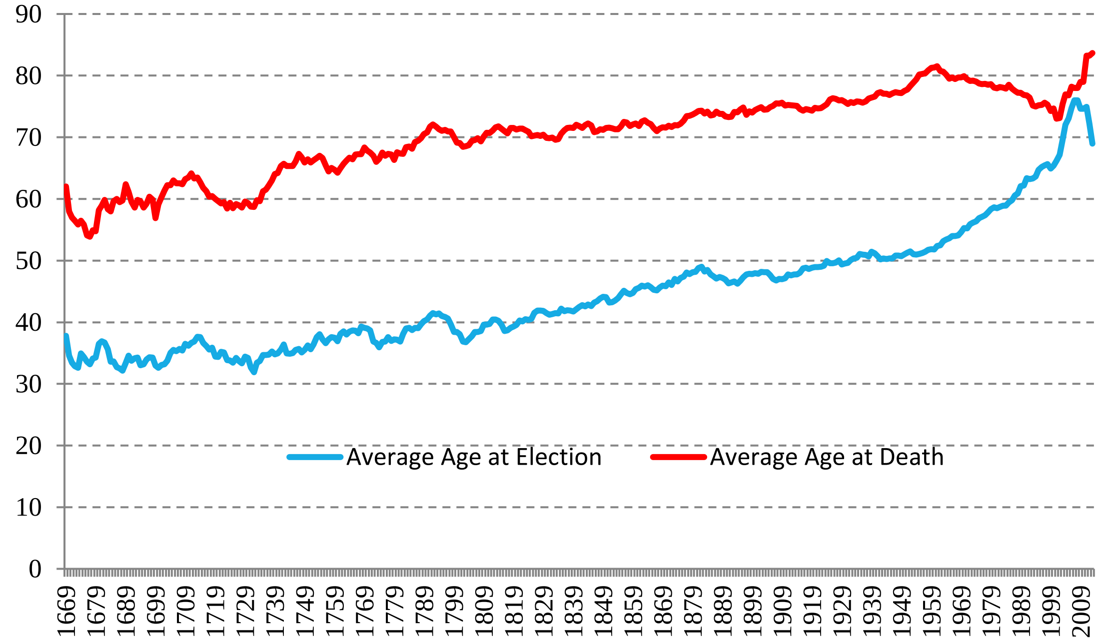


Table 2.6: RSA Premiums 1754-1776

	Cash Premiums	Gold Medals	Silver Medals	Gold Pallets	Silver Pallets
Agriculture	3,202	56	26		
Chemistry	1,315	2	1		
Colonies and Trade	2,786	12			
Manufactures	2,026	1	3		
Mechanics	2,285	6	10		
Polite Arts	8,326	10	6	17	84
Miscellaneous	3,613	16			
Total Premiums	23,552	103	46		
Cost of medals	*24,616*				
Total Cost of Prizes	48,168				

KAIs and Network Effects

As explored in the Romer-Mokyr model, KAIs reduced the cost of access to fragmented knowledge bases, raising the average productivity of R&D. They achieved this by lowering the cost of communication within the R&D community, increasing the network's average *degree* and *connectivity*, as discussed above (Jackson 2010). This facilitated innovation via three channels:

1. Knowledge Diffusion Rates and Search Costs: Network theory has established the efficacy of 'small-world' social networks in permitting the diffusion of information through society and reducing knowledge search costs relative to other societal structures (for example, see Granovettor 1973, Cowan & Jonard 2003, or for a textbook treatment oriented towards economics, Jackson 2010). A small-world network is one in which individuals are locally connected within cliques, while a small number of connections connect cliques together. KAIs created such a social structure within the British scientific and technological community. The hierarchical 'hub and spoke' structure of core KAIs discussed above – of national elite, local elite and ordinary local KAIs – along with shared membership across regions and hierarchical levels, bridged geographic and social distance across scientists, inventors and entrepreneurs from different walks of life. Musson and Robinson (1968) describe the network from the perspective of the Manchester Literary and Philosophical Society in the 1780s, illustrating the society's national and trans-European correspondences with scientists and industrialists, the numerous Fellows of the Royal Society among its ordinary attending membership and its seminal role in the foundation of educational institutions in the city and wider region, such as the Manchester College of Arts and Sciences and dissenting academies such as Manchester Academy. Robert Schofield describes the rich scientific and industrially oriented networks of the Lunar Society in Birmingham (Schofield 1957) and Ian Inkster reveals a similar structure to Manchester in other English cities (Inkster 1997).

As a large network with a cultural bias towards science, Freemasonry supported the network established by core KAIs. One of the founders of the movement was leading Newtonian, Desaguliers. Figure 2.24 shows the number of Freemasons who were Fellows of the Royal Society over time based on a list of *FRS* Freemasons on the website of the London Museum of Freemasonry[38]. In figure 2.25, I denominate this figure by concurrent Royal Society membership to show the percentage of Royal Society Fellows who were Freemasons. Throughout the British Industrial Revolution around 10% of *FRSs* were Freemasons. Freemasonry may have had a significant effect in helping to connect the central node of the KAI infrastructure with the rest of the scientific, technological and business community.

A prominent example of the KAI network facilitating the search for expertise was the invention of the Davy lamp in 1815. Following an accidental mining explosion in Newcastle, local KAIs contacted chemist Humphry Davy of the Royal Institution in London to design the would-be famous safety lamp (Jacob 2014). Such long-range interaction became more common over time as the KAI infrastructure matured, as figure 2.26 illustrates. Using the dataset of British patents during the Industrial Revolution constructed for this thesis and discussed in chapter 3, I calculate the proportion of joint patents over time whose co-patentees resided in different counties across Britain (excluding patents with any London patentees as these were sometimes patent agents). There is a very marked upward trend from around one-tenth in the early decades of the Industrial Revolution to about one third by the 1840s.

[38] http://www.freemasonry.london.museum/os/wpcontent/resources/frs_freemasons_complete_jan2012.pdf

Figures 2.23: Number of Freemasons who were Fellows of Royal Society

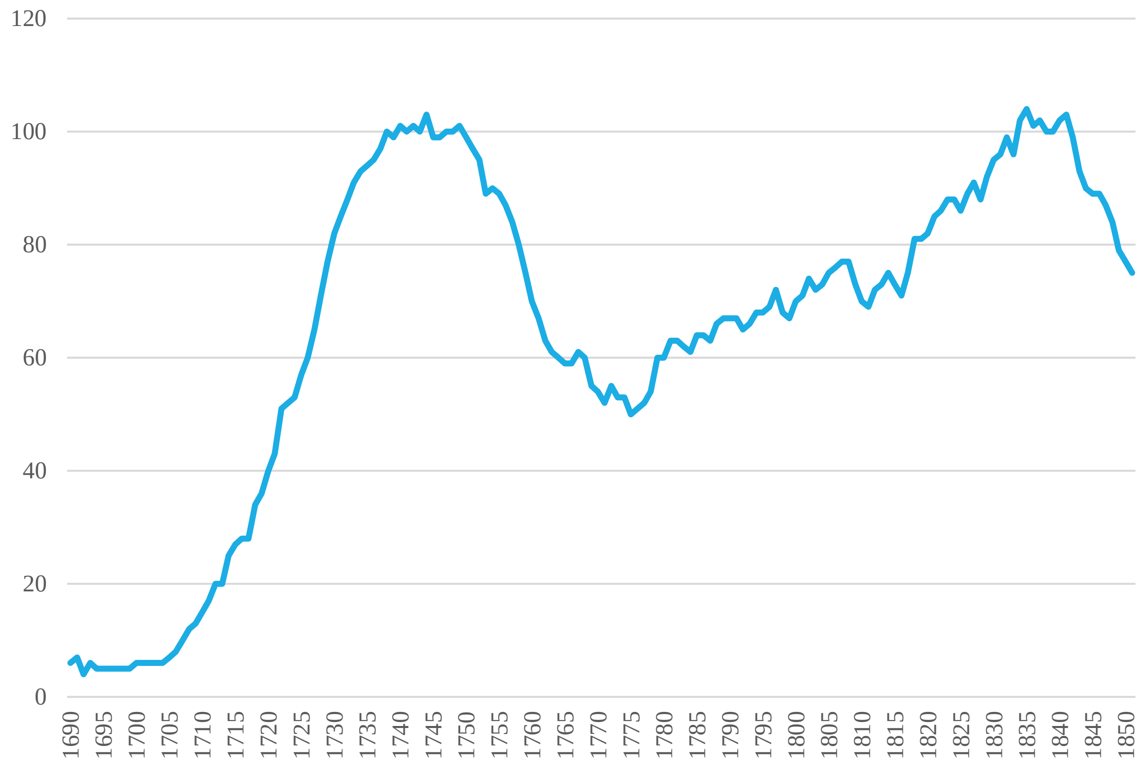


Figure 2.24: Percentage of Fellows of the Royal Society elected during previous 10 years who were Freemasons

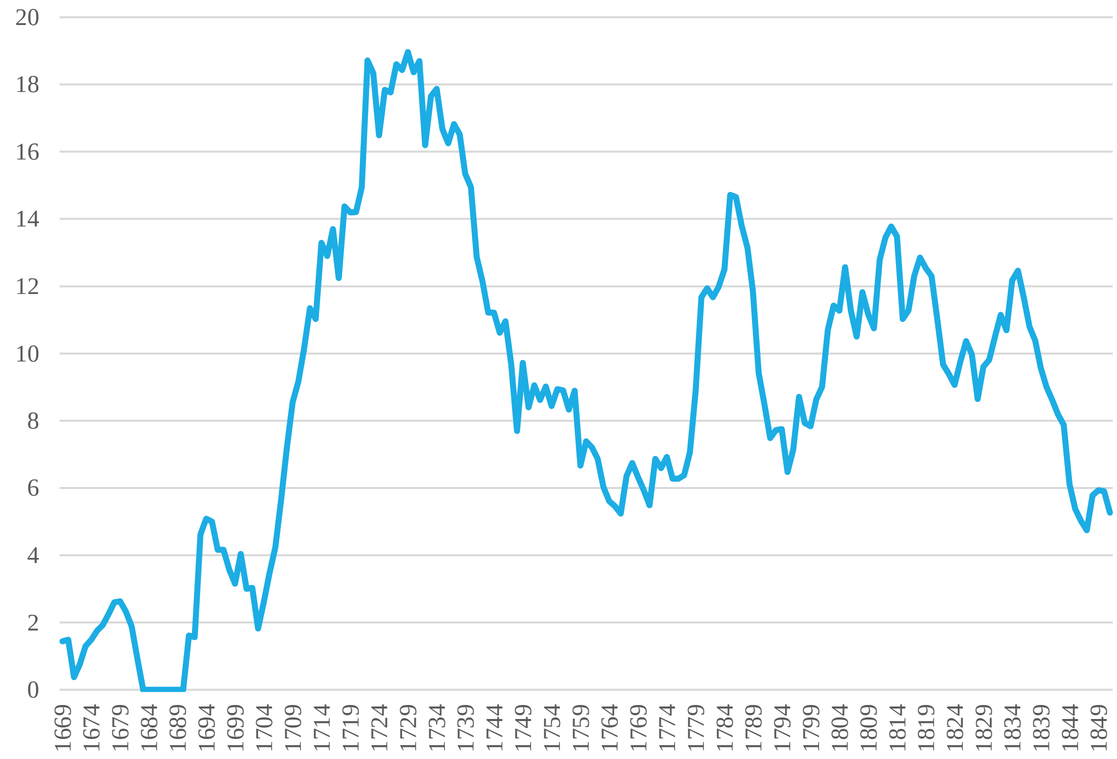
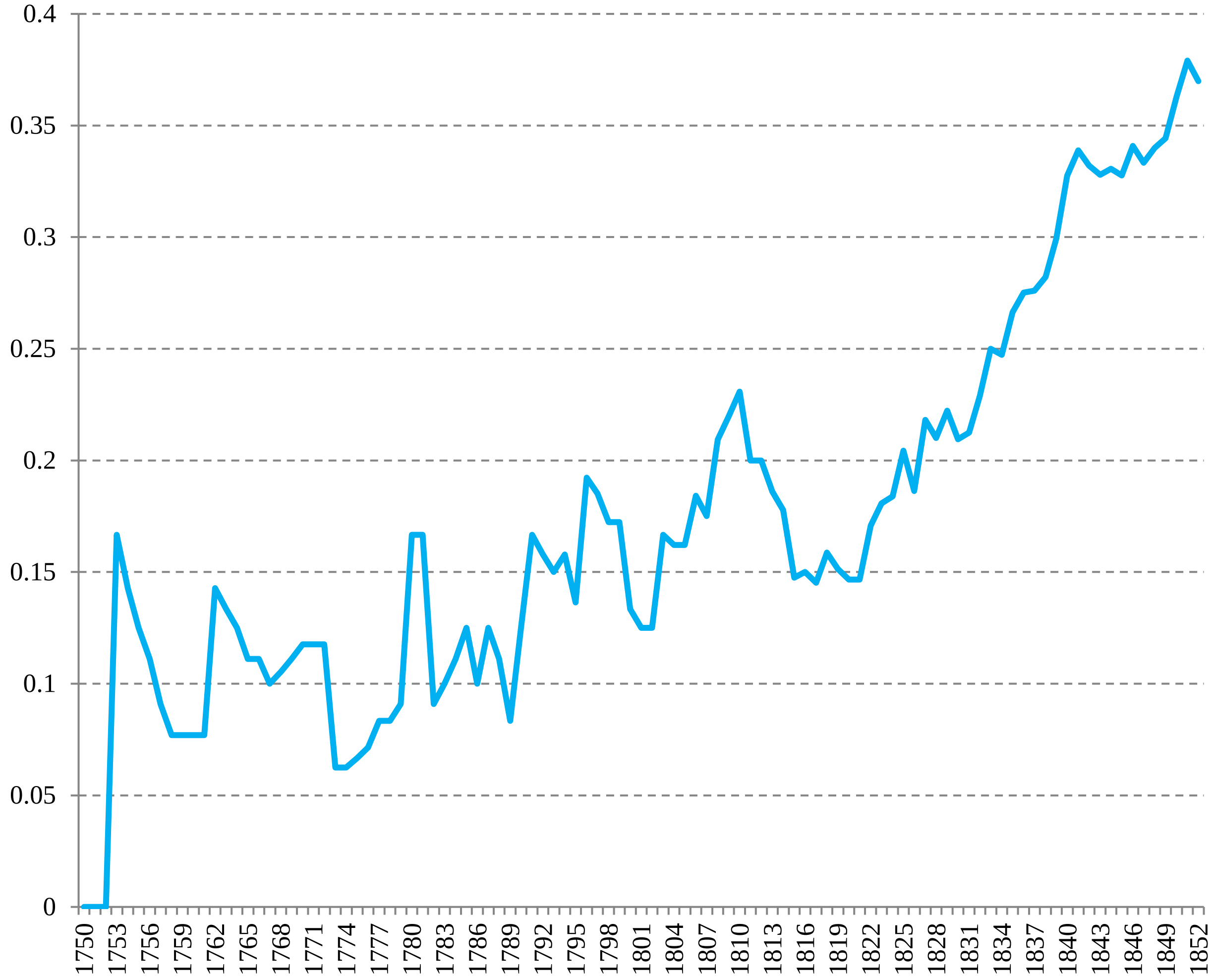


Figure 2.25: Share of joint patents whose co-patentees live in different counties (London patents excluded) (20 year, centred)



2. Collaboration and Knowledge Recombination Effects: Core KAI membership was cross-occupational, rather than divided along occupation or industry lines. This had two implications for innovation. First, there was little product market competition between members, which meant that they were more likely to share information and collaborate, as Lawrence Katz's model of R&D consortia predicts (Katz 1984). Indeed, Wedgwood tried to set up an industry-specific R&D consortium-type KAI in 1775 but the project failed due to disagreement among the prospective members about how to share the profits of innovation (Schofield 1957). Mixed occupations also circumvented the incentives of members of the same occupational group to stifle innovation to preserve shared rents, which Ogilvie (2014) documents in the case of medieval guilds.

Second, interaction between occupational groups increased the scope for 'recombinant innovation', in which new innovations are based on a combination of existing technologies from multiple industries. The canonical example in the British Industrial Revolution was Henry Cort's invention of the puddling and rolling process, already mentioned above, which combined reverberatory furnaces used in glass making with mill rollers. Leonard Dudley argues that the innovations that characterise modern economic growth are differentially dependent upon collaboration, crediting the increased scope for communication through shared language and literacy as a determinant of modern economic growth (Dudley 2012). Akcigit, Kerr and Nicholas (2013) show using patent citation data that recombination is conducive to high quality innovation. Likewise, De Vaan, Vedres and Stark (2015) show that recombination lies behind blockbuster innovations in the computer games industry, while Uzzi et al. (2013) have shown that cross-disciplinary teams of scientists produce particularly high quality research.

Figure 2.26: Letter from Erasmus Darwin to Matthew Boulton, 1783/03/04

Derby Mar. 4-83

Dear Sir

I am favour'd with your letter, and the note for 30£. In respect to the principle I should not have written to you for it, but that I supposed the income from your Engins would have render'd it not inconvenient to you to return it. When you can do it therefore conveniently, do so.

We intend to pass this Summer at Radburn, where Mrs D. and myself shall be very happy to see you, and yours; in the Autumn we design to return to Derby to reside <u>for good</u> (I hope) as they say.

<u>We have establish'd an infant philosophical Society at Derby, but do not presume to compare it to your well-grown gigantic philosophers at Birmingham. Perhaps like the free-Mason societies, we may sometime make your society a visit, our number at present amounts to seven, and we meet hebdomidally.</u>

<u>I have repeatedly spoke of you Engins to Arkwright's friends, and hope you may still be employ'd, but know very little at present of the matter. I suppose you use your reciprocating engine for working corn-mills, and not your circular one?</u>

Pray bring you Son to see us at Radburn sometime this Summer, that we may renew our early acquaintance. I wish you would bring a party of your society and hold one Moon at our house.

NB. our Society intend to eclipse the Moon on the 18 of this month, pray don't you counteract our conjurations. I beg to be remember'd to all the Insane at your next meeting, and am dear Boulton, your affect. friend and obed. serv.

E Darwin

3. Social Capital Effects: Small-world networks also facilitate the flow of reputational information and gossip. They raise the cost of defection within business transactions, thereby increasing the level of social capital, or the scope to trust other members of society (Dasgupta 2005). Laursen et al (2012) show using data on modern day Italy that social capital has a positive effect on the localised rate of innovation. By generating a small-world social structure KAIs must have had a positive impact on social capital within the innovation process. An interesting example is illustrated by figure 2.27, a letter from Erasmus Darwin to fellow member of the Lunar Society Mathew Boulton. Darwin was acting as the middle-man between Boulton and Watt and some potential customers with whom Darwin had recently formed another KAI in Derby. Watt had previously had an acrimonious relationship with the firm, which Darwin repaired.

Britain's Industrial Revolution KAIs versus Twentieth Century Innovation Institutions

Although Britain's eighteenth and nineteenth century KAIs represented a giant leap forward as innovation institutions they were inferior to those of the twentieth century, namely research universities, corporate R&D departments and government research and funding bodies. Although none of these three has proved to be without its flaws, the strength of the modern innovation system lies in their nature as mutual complements.

Different R&D projects suit different institutional approaches. The most appropriate approach generally depends on the degree of technical specialisation required, the difficulty of the appropriation of returns and the funding requirements. In principle, a project may be so challenged in any one of these dimensions that it cannot proceed at all. However, the à la carte menu of modern innovation institutions has risen to these challenges much more effectively than KAIs could on their own during the eighteenth and nineteenth centuries. As such, they have likely processed a much larger proportion of prospective R&D projects than KAIs did during the British Industrial Revolution, generating a higher rate of technological progress.

First, modern innovation institutions have achieved a much finer division of labour giving rise to greater expertise, including a division between propositional knowledge acquisition in research universities and prescriptive knowledge acquisition in corporate R&D

departments, fitting the incentive structures of the two institutions (Brookes 1994). The benefit of specialisation also includes a more rigorous filtering and validating of propositional knowledge. More expertise and better validation have sped up the rate of accumulation of propositional knowledge.

Second, twentieth century innovation institutions have offered a wider set of solutions to profit-appropriation problems, which in turn has encouraged innovative effort. David Teece (1986) argues that the returns to innovation can often only be appropriated through the ownership of complementary assets. The invention of the large scale 'modern industrial enterprise' around the turn of the twentieth century has enabled such ownership through vertical integration (Chandler 1990). The large corporation also helps the innovator to maximise his first mover advantage by enabling him to produce at large scale, providing cost and brand advantages (Chandler 1990, Teece 1993). Acs, Economidou and Sanders (2009) show the benefits of vertical integration within an endogenous growth model. In the absence of the large industrial enterprise during the British Industrial Revolution, the appropriation of innovation returns was more difficult. As Harley shows for the textile industry, industries expanded rapidly following technological innovation, but industry growth occurred via firm entry rather than the growth of technological leaders and the prices of output fell rapidly (Harley 2012).

Third, twentieth century innovation institutions have delivered much greater funding for R&D than KAIs could during the British Industrial Revolution. Cleary, much greater government taxation and expenditure as a share of the economy in general has played a large role, but so too has the division of financing between the government and the private sector. As chapter 4 explores, the government finances a disproportionately high share of basic research into propositional knowledge, while the private sector tends to finance more downstream R&D. In doing so, large corporations have been better able to cross-subsidise R&D with revenues than small firms were during the British Industrial Revolution (Chandler 1990). Rising financing requirements appear to have set in during the nineteenth century due to the advance of capital intensive experimental science, as Crosland and Galvez (1989) show in the French context. The state-funded French Academy of Sciences responded to the increased demand for working capital in R&D by re-allocating financial resources away from prizes, which had traditionally served as the basis of R&D funding, towards research grants. British KAIs did not respond so adeptly.

In an interesting twist, since the beginning of the twenty first century, new R&D activities have emerged that resemble those of KAIs during the British Industrial Revolution. Large investments by large firms in their internal R&D departments are being increasingly displaced by so-called “open innovation”, the reliance upon external sources of innovation, such as academic technology specialists, other firms or independent inventors (Chesbrough 2003). Arora, Cohen & Walsh (2014) find from a survey of 6,000 US manufacturing firms that of the 16% that had innovated, 49% reported that their most important innovation came from an outside source. This shift is likely due to three factors. First, the internet is a complementary technology to open innovation, lowering communication and knowledge transfer costs. Second, innovation within the IT industry has represented a highly disproportionate share of overall innovation and appears to be particularly conducive to open innovation, via the ‘open source’ development of software by collaborating communities of programmers. Third, innovation in the IT sector tends to require lower capital outlays, leading to the converse of the rise in required outlays experienced moving out of the age of KAIs in the late nineteenth and early twentieth century.

To some degree, this trend validates the activities of eighteenth and nineteenth century KAIs. Nevertheless, open innovation today represents just one of the numerous options on the menu. This menu caters much better for the idiosyncratic challenges faced by inventors, whether due to the depth of knowledge required, uncertainty regarding the appropriation of returns or the need to secure finance. Given the superiority of the twentieth century innovation infrastructure compared to the prototype offered by Britain’s eighteenth and nineteenth century KAIs, it is not surprising that the rate of technological innovation achieved at the technological frontier during the twentieth century was greater than that achieved during the British Industrial Revolution.

Conclusion

I have shown in this chapter that Britain’s network of KAIs became a substantial institutional infrastructure during the British Industrial Revolution. I have argued that KAIs gradually lowered the cost of access to knowledge in Britain, thereby raising the productivity and supply of British R&D and that, as such, they can help us explain the gradual emergence of modern economic growth during the British Industrial Revolution. At the same time, KAIs lacked important capabilities that the institutions that replaced them in the twentieth century possessed, so the transition to these institutions can help explain the further acceleration of economic growth in the twentieth century. In the next chapter, I present empirical tests of the influence of KAIs on technological innovation.

Appendix: Sources for the Knowledge Access Institutions Database

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- The Yearbook of the of Learned Societies of Great Britain (1884, 1885, …, 1930), vols:1884-1930, London, Griffin

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- University of Waterloo, *Scholarly Societies Project* http://www.scholarly-societies.org/

Chapter 3

Did Knowledge Access Institutions Facilitate Modern Economic Growth? An Empirical Investigation

Did Knowledge Access Institutions (KAIs) contribute systematically to the acceleration in technological innovation that characterised the British Industrial Revolution? This chapter provides falsifiable evidence that suggests so. The empirical strategy used to identify this contribution rests on the assumption that the effect of a KAI on innovation would be stronger within its locale than further away. This assumption follows from two observations. First, as explained in chapter 2, KAIs raised the rate of technological innovation by reducing the cost of access to knowledge. Second, the cost of access to knowledge is an increasing function of geographical distance from the source (see Barthelemy 2011 for a survey). Together these observations imply that the regional distribution of KAIs would have influenced relative regional knowledge access costs and rates of technological innovation. Moreover, the economics literature on 'knowledge spillovers' shows that in the modern economy the flow of technological knowledge is spatially mediated (see Audretsch and Feldman 2004 for a survey). During the eighteenth and early nineteenth centuries, before the introduction of modern transportation and communication technologies, it would surely have been even more spatially mediated.

As such, this chapter asks: was the rate of technological innovation during the British Industrial Revolution faster close by KAIs than further away? Did local rates of technological innovation accelerate in relative terms when KAIs were introduced in the vicinity? To answer these questions, I carry out three studies of the link between the spatial-temporal distributions of KAIs and technological innovation during the British Industrial Revolution and the period of the nineteenth century emergence of modern economic growth in the United States. These studies use new datasets of proxies for the spatial-temporal distribution of technological innovation during the British Industrial Revolution based on all English patents granted to British residents between 1617 and 1852 and all British exhibitors at the Great Exhibition of 1851, and for the US case, all American patents granted up to 1873. In each case, observations are geocoded based on the patentee or exhibitor's address and grouped by discrete regional units to create panel datasets of proxies for the rate of technological innovation. I match this data with the dataset on KAIs introduced in chapter 2, along with control variables, and use econometric methods to test if the spatial-temporal patterns of technological innovation can be explained by the location and timing of KAIs.

I find that local rates of patenting during the British Industrial Revolution were responsive to the local prevalence of core KAIs. This indicates an association between core KAIs and R&D/innovative effort. Furthermore, the prevalence of core KAIs also influenced average patent quality, indicating an association between core KAIs and R&D productivity. These results support the two main predictions of the Romer-Mokyr model in chapter 2. They are supported by a cross-sectional study of core KAIs and exhibitors and prize winners at the 1851 Great Exhibition. British registration districts with greater numbers of core KAI members sent more exhibitors and won more prizes at the exhibition. Likewise, agricultural innovation appears to have been responsive to core agricultural KAIs in the mid-nineteenth century United States, with similar elasticities observed to the British industrial case. In general, the effect of peripheral KAIs on innovation is not detected. This may be due to a low *marginal* elasticity of innovation with respect to libraries, masonic lodges and booksellers.

Theory: The Spatial Relationship between KAIs and Technological Innovation

Consider an *n*-region version of the Romer-Mokyr model from chapter 2, dropping the simplifying assumptions that regional propositional knowledge sets are perfect complements and of equal size. Let *m/n* be the proportion of regions with at least one KAI (i.e. *m* regions have a KAI, *n-m* do not).

The rate of technological innovation in region *i* in the presence of a KAI is proportional to:

$$\frac{d{\lambda_i}^{KAI}}{dt} = \delta^{KAI} L_{R_i}[\Omega_i \cup \bigcup_{j \neq i}^{m \leq n} \Omega_j]$$

Conversely, without a KAI, the rate of technological innovation in region *i* is proportional to:

$$\frac{d\lambda_i}{dt}^{NO\ KAI} = \delta^{NO\ KAI} L_{R_i} \Omega_i$$

The marginal effect of region *i*'s first KAI on the local rate of innovation is positive for two reasons. First, the productivity of research in region *i* increases, since $\delta^{KAI} > \delta^{NO\ KAI}$, owing to the influence of 'scientific R&D', as described in chapter 2. Second, researchers in region *i* now have access to the propositional knowledge sets of all *m* regions, which represents a fall in knowledge access costs so long as $m > 1$ and the other $m\text{-}1$ regions have non-zero propositional knowledge sets. This term captures the network effects of KAIs on technological innovation described in chapter 2.

Clearly, identifying these effects requires controlling for confounding variables, such as differences in the allocation of innovative effort over space and time. As such, it is desirable to use within-region estimation, which enables one to control for time invariant characteristics, and time fixed effects to control for the national trend over time.

Empirical Strategy: Distance and Access to Knowledge

Regional variation in knowledge stocks assumes that the cost of accessing knowledge held only in region *i* is lower for an inventor residing in region *i* than region *j*. The positive relationship between distance to source and the cost of knowledge access is the key to the empirical strategy of this chapter. What evidence exists that it holds?

There are three types of evidence. First, the 'knowledge spillovers' literature has illustrated the spatial mediation of knowledge flows within the process of technological innovation in the modern economy. Knowledge spillovers represent an inventor's exploitation of another agent's knowledge base. The source agent may be, for instance, a research university or corporate R&D department. Knowledge spillovers tend to be localised in nature: inventors based further away from the producer of a unit of knowledge are less likely to utilise it, even after controlling for the spatial distribution of economic activity. The seminal contribution to the literature was Griliches' (1979) 'knowledge production function', which modelled regional innovation outputs, e.g. patents, as a function of regional knowledge inputs e.g. corporate R&D expenditure and university research. Using this model, Pakes and Griliches (1984) and Jaffe

(1986, 1989) showed that patenting rates across US states could be explained by state-level corporate R&D expenditure and university research of agents other than the patentees. Subsequent studies strengthened the identification of localised knowledge flows by examining spatial data on patent citation pairs. These studies showed that patent citations were systematically biased towards other local patents, even after controlling for industrial location (e.g. Jaffe, Trajtenberg & Henderson 1993, or see Audretsch & Feldman 2004 for an authoritative survey), suggesting that locally produced knowledge is more accessible than knowledge produced further away. More recently, Cowan and Zinovyeva (2013) have tested the effect of an exogenous supply of knowledge inputs on local technological innovation in the form of the national policy-led expansion of the Italian university system between 1985 and 2000, finding a large effect.

Second, Jasjit Singh (2005) and Stefano Breschi and Francesco Lissoni (2009) have examined the link between the spatial and social mediation of knowledge access. By matching data on patent citation pairs to data on connections between inventors, based on past research collaborations, they show that the local bias of social connections explains most of the spatial mediation of patent citations. Knowledge tends to flow between individuals residing close to one another because those individuals know one another, not merely because they are subject to the same local stimuli.

Third, recent studies have used large-scale spatial datasets based on online social networks, mobile phone calls and emails to illustrate the generality of the spatial embeddedness of social connections. For example, using data on the locations of users of *Facebook* in the US, Backstrom et al. (2010) find that the probability of a connection between two users declines rapidly as distance between them increases. This can be summarized by the formula $Prob(\text{friendship}) = (0.2 + x)^{-1.05}$, where x is distance in miles. This result holds beyond Facebook connections. Goldenberg and Levy (2009) obtain a similar result, i.e. a decay exponent for the probability of connection of the order of -1, using the IP addresses of email pairs in the US. In the case of inventors, Cerina et al. (2014) show using data on joint patentees (controlling for inventors working for the same institution) that the probability of connection also decays by distance with a decay exponent of around -1. Using data on phone call pairs, Sobelevsky et al. (2013) illustrate the strongly localised nature of mobile phone communication in Great Britain. Relatedly, Gonzalez, Hidalgo and Barabasi (2008) illustrate the strongly localised nature of individual geographical mobility. They show that the probability of an individual making a phone call from any location decays as a function of the distance of that location from that of the individual's modal location. The distance decay exponent of -1.75 captures a somewhat steeper decay than between-person connections. This is as one would expect, since one is likely to substitute physical travel for remote communication as distance increases.

This evidence reveals that locally produced knowledge is more accessible than knowledge produced further away and that this is because social networks are spatially embedded. Moreover, the spatial embeddedness of social networks is general, so we should expect knowledge access to be spatially mediated in general. Indeed, the spatial mediation of social networks and limits to individual geographical mobility would surely have been much greater during the British Industrial Revolution and in the mid-nineteenth century US than during modern times owing to the much higher transport and communication costs that prevailed prior to the full expansion of the rail network and the introduction of the telegraph, telephone, automobile, air travel and the internet.

Study 1: KAIs and Patenting during the British Industrial Revolution

This study investigates whether the regional prevalence of KAIs affected regional patenting rates and quality during the British Industrial Revolution. It uses a panel dataset of all patents filed under English jurisdiction by British residents between 1757 and 1852 grouped by county and census registration district in ten year intervals. This dataset is matched to data on core and peripheral KAIs introduced in chapter 2. Panel data on population and, for some cross-sections, manufacturing employment, are also matched to act as controls. I estimate within-region to help reduce potential bias from omitted variables.

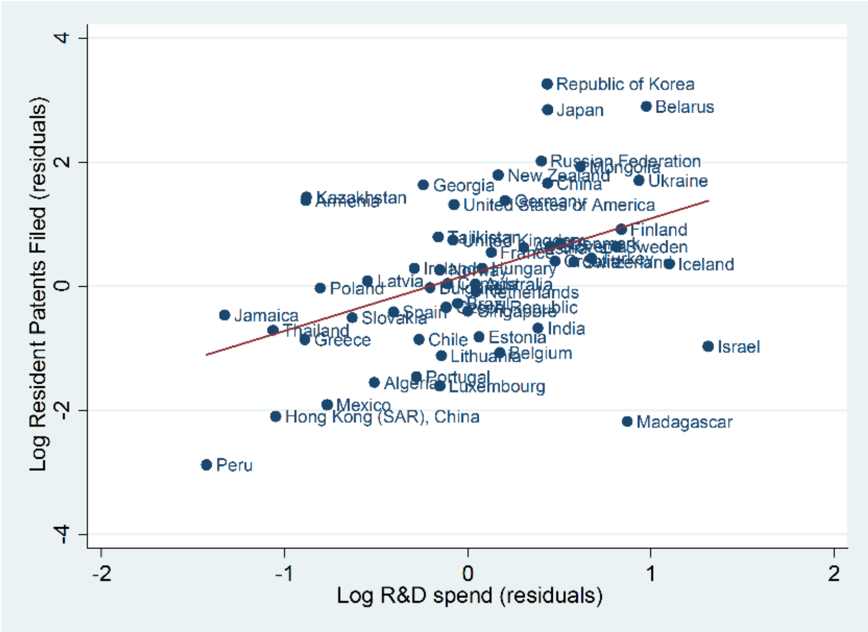
The strength of this study is that it observes the overall period of the British Industrial Revolution as conventionally dated. However, it suffers from two weaknesses. First, the set of controls included is quite sparse owing to the lack of available data. Regional fixed-effects mitigate this weakness somewhat and an additional two-period 'long panel' is constructed specifically to allow for the inclusion of a manufacturing employment variable as a control for industrialisation, nevertheless, more controls would have further helped identification. Second, the use of patent counts as an indicator of the rate of technological innovation suffers from well documented flaws, and should always be interpreted with caution (Griliches 1990, Hall 2013). The main problems are that not all innovation is patented and not all patents represent valuable innovation. Since not all innovations are patented, differences in the propensity to patent over space and time may give rise to observed differential patent counts that do not reflect differential innovation. In the cross section, the problem arises when comparing across different patent jurisdictions, which can introduce significant differentials in the costs and benefits of patenting due to differences in patent fees, the time-demands of the application process and the size of the addressable market covered by the patent. In time series, the problem arises when reform of the patent system materially changes the costs and benefits of patenting over time, the cost or availability of patent services (such as patent agents or lawyers) changes over time, or the growth of the market raises the return to inventions.

This study observes a single patent jurisdiction that underwent no reforms or fee changes during the period under consideration. Patentees increasingly used agents during the latter eighteenth century, cutting down the length of the application procedure possibly from around six months to two months. However, this was an expensive service to procure, adding a further £40 to £100 of cost to the £100 patent fee, compared to an average skilled worker's weekly wage of between £1 and £2. As such, it is not clear that this represented a significant average cost reduction (Bottomley 2015). Market size increased over time due to the growth of the economy.[39] However, this was a national-level factor which can be controlled for in a within-region estimation framework by using time fixed effects. Likewise, within-region estimation enables one to control for time invariant regional influences on the relative propensity to patent, such as distance to London, which would have affected patentee transaction costs[40].

[39] (though note that Richard Sullivan has found that the elasticity of patenting to market size during the nineteenth century was much lower than during modern times (Sullivan 1994)

[40] Some influence will remain if relative geographical propensities to patent change over time.

Figure 3.1: Partial correlation across countries in 2006 of resident patent filings and R&D spend, controlling for GDP and population (data from WIPO)



How problematic valueless patents prove to be depends on the research question at hand. If patenting is not trivially cheap then even valueless patents represent a significant outlay of innovative effort. As figure 3.1 shows, there is a strong partial correlation between patenting rates and R&D expenditure across countries in 2006[41], controlling for GDP and population. This indicates a strong relationship between innovative effort and patenting rates, even despite differences in national patenting jurisdictions. Patenting in England during the Industrial Revolution was expensive, as mentioned above and explored in more detail in chapter 4. Therefore, patent counts are likely to capture variation in innovative effort, as it features in the Romer-Mokyr model.

To capture variation in the productivity of innovative effort, I employ a measure of patent quality for English patents prior to 1852 advocated by Alessandro Nuvolari and Valentina Tartari (2011). This is based on a count of references to each patent in the contemporary technological and legal literature discussed below. Finally, to circumvent patent data concerns entirely, study two below uses data on technology exhibits rather than patents.

[41] using data from the World Intellectual Property Organisation

KAIs and Patenting during the British Industrial Revolution: Data

I have constructed a dataset of all English patents registered by British residents from 1617, the year of the first registered patent, to 1852, the year of the first substantive reforms to the patent system. An aggregate annual time series of registered patents and a 10-year moving average are shown in figure 3.2, however, the original feature of the dataset is the spatial coding of patentee residences to enable regional disaggregation. The dataset was constructed by manually entering information from the *Titles of Patents of Invention Chronologically Arranged, 1617–1852* (Woodcroft 1854), located in the British Library, into a spreadsheet and geocoding the addresses of patentee residences. I convert residence information, which in most cases includes parish, village, town or city and county to British Ordnance Survey co-ordinates using data kindly provided by Tim Leunig at LSE and a matching algorithm between addresses and corresponding degrees of latitude and longitude, supplied by http://www.geonames.org/. Where place names taken from the *Chronological Index* were unsuccessfully matched by this method because of the use of historical spellings or defunct place names, I assigned co-ordinates manually using *Google Maps*. I use GIS software to convert latitudinal and longitudinal co-ordinates to kilometres east and north from a fixed point located south-west of the British land mass, as per the convention of British Ordnance Survey coordinates (referred to as 'easting' and 'northing' coordinates). This conversion adjusts for the curvature of the Earth.

I match each patent with its entry in the *Reference Index of English Patents of Invention, 1617–1852* (Woodcroft 1855), from which a patent quality index can be derived, as shown by Nuvolari and Tartari (2011). This *Reference Index* was compiled in 1855 by Bennet Woodcroft of the British Patent Office and contains a list of citations in technological and legal publications for each patent. Nuvolari and Tartari argue that although the index is subject to sources of noise, it contains information about the relative quality of individual patents. For example, they show that it assigns high scores to historically important patents. The index is particularly useful if used to estimate the average quality of a group of patents, reducing idiosyncratic noise at the individual patent level. Nuvolari and Tartari de-trend Woodcroft's original count index to control for time heterogeneity. Following their approach, I apply a Hodrick-Prescott filter (with lambda=6.25) to the annual average of Woodcroft's simple count index and divide each patent's count by the value of the time-trend in that year. Then, because of the highly non-linear distribution of references across patents, as illustrated in figure 3.3,[42] I create a binary indicator of patent quality in which the top 10% of patents based on the de-trended index are coded to equal 1, representing 'top patents', and the bottom 90% are coded to equal 0.

Figure 3.2: English Patent Applications by British Residents, by Year 1617-1852

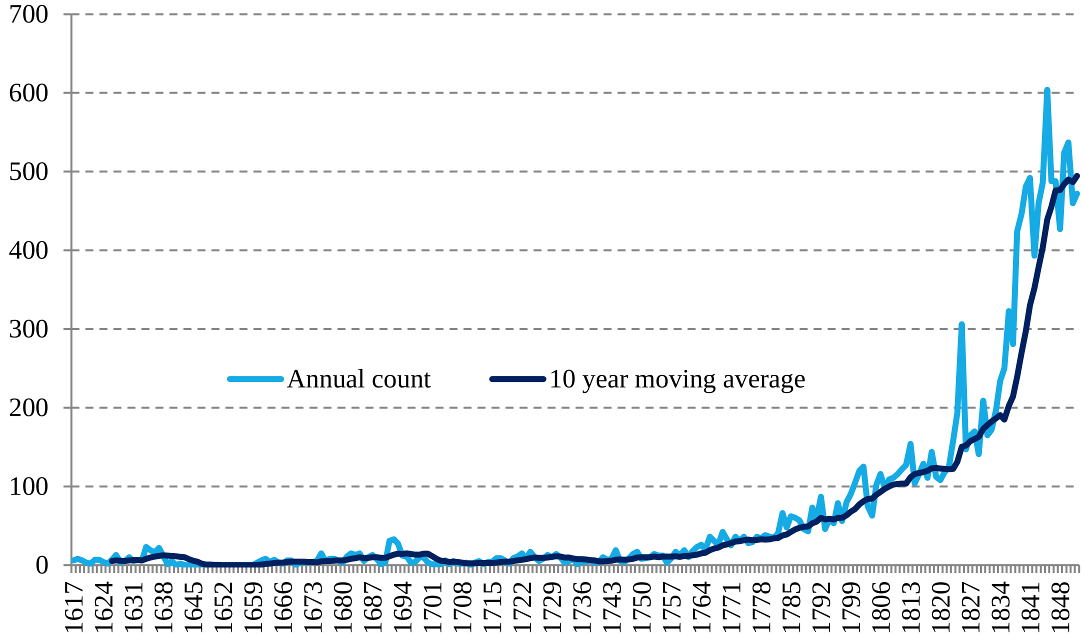
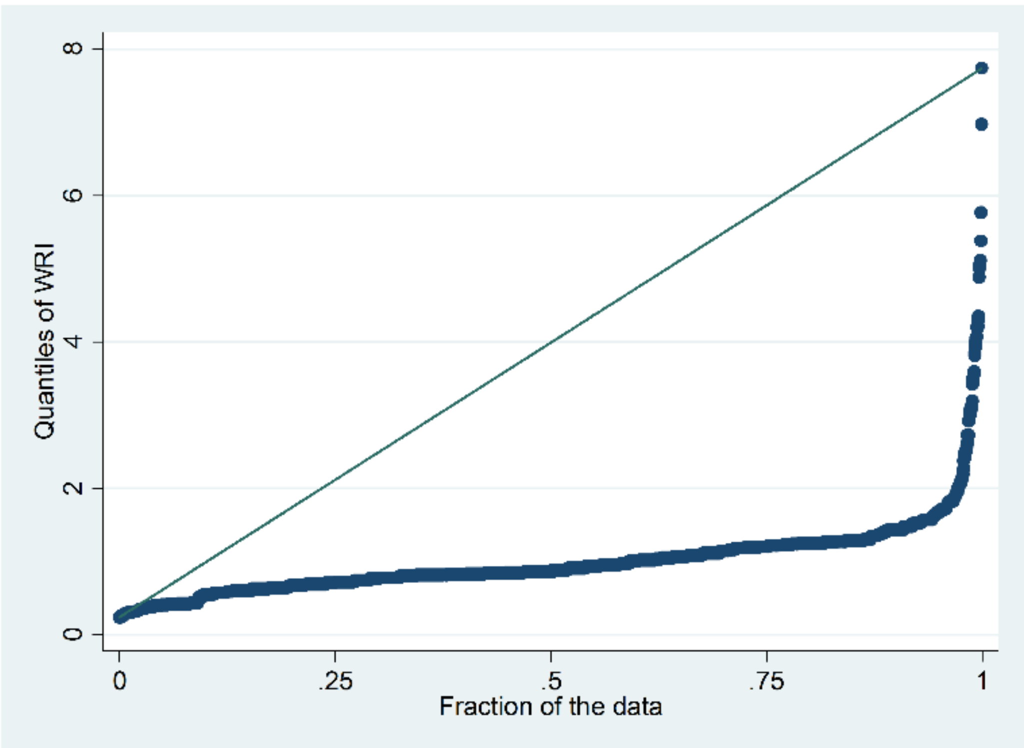


Figure 3.3: the distribution of continuous weighted Woodcroft Reference Index



[42] which matches the pattern of modern citation distributions (Hall, Jaffe & Trajtenberg 2000)

Fields included in the dataset are: year of patent, patentee name, patentee address (town/village, county, street if in London), geocoded co-ordinates of patentee address, patentee occupation, industrial sectors to which the patent applies (not a unique field, i.e. a patent may apply to more than one industrial sector), a brief description of the patent and the binary patent quality measure described above based on the Woodcroft Reference Index. I construct the dataset at the level of patentee, and include separate observations where there are multiple patentees for a single patent.

I derive from this individual patentee-level dataset, two region-period panel datasets. The first is a county-decade panel, which includes all 86 English, Welsh and Scottish counties covering Great Britain. The decade counts for each county are centred in ten year intervals around the years 1761, 1781, … , 1851, and include the patents filed between years *t-5* to *t+5* inclusive, except for the count centred on 1851 which is truncated in 1852 because of substantive reform of the system in that year which may have affected the comparability of observations beyond this date. The overall observation period 1756 to 1852 provides good coverage of the conventional dating of the period of the British Industrial Revolution. The second panel is a 'long-panel' of two cross-sections of the 586 English and Welsh census registration districts centred on 1817 and 1851. I group registration districts in London together due to the indeterminacy of the registration district level location of many of the KAIs within London in the dataset[43]. This panel was constructed to exploit the availability of data on sector-specific employment for these years, as discussed below.

Table 3.1 displays patents per capita by English county-decade, expressed as a percentage of the contemporaneous London count in each decade. As the British Industrial Revolution progressed, patenting rates in Lancashire, Warwickshire, Staffordshire[44] Leicestershire and the East Riding of Yorkshire made up ground on London. Nevertheless, London held on to its dominance throughout the entire period, Warwickshire getting the closest at around 60% of the London rate from 1811 onwards. Figure 3.4 displays the geographic distribution of patents per capita in 1761, 1801 and 1851.

[43] Hence, the overall number of registration districts is reduced from 623 to 586.

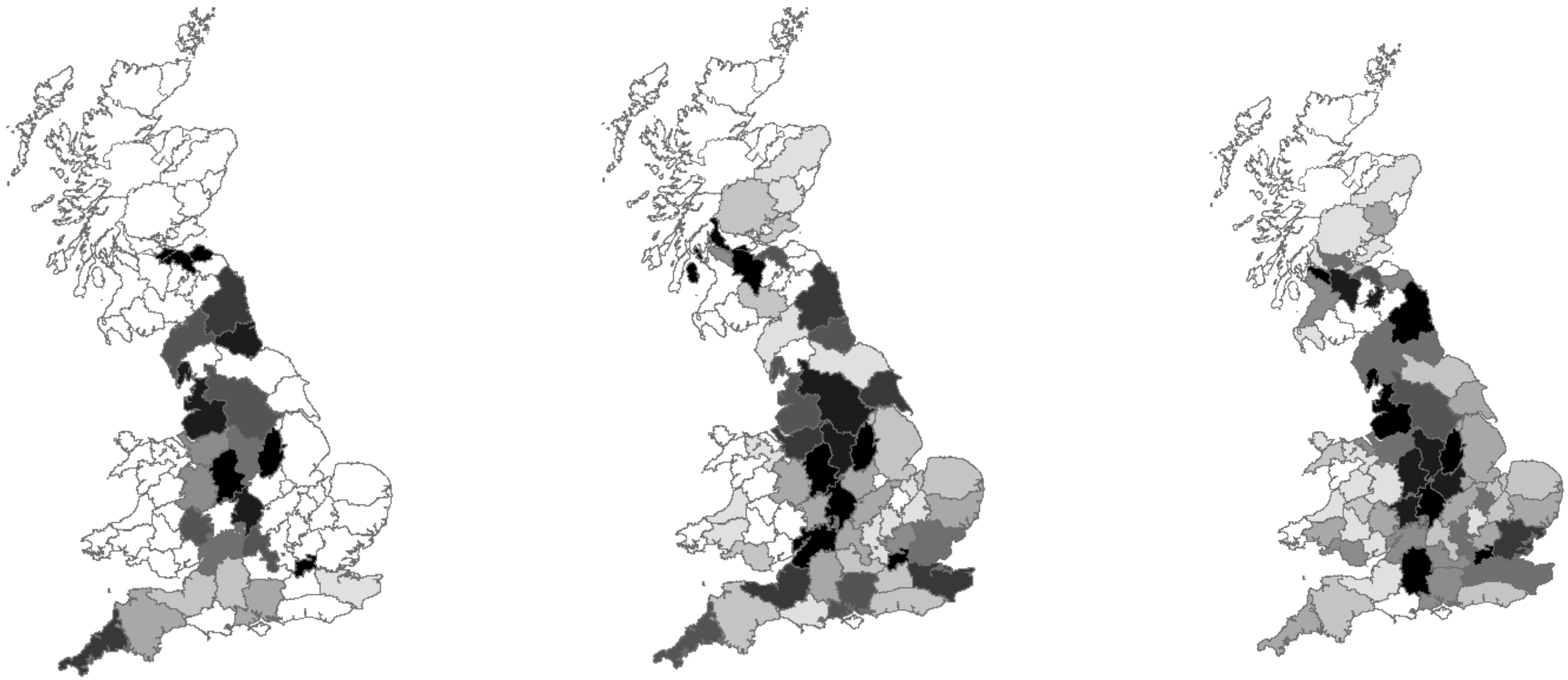
[44] discounting its high starting rate in 1761's which had fallen by 1771

Table 3.1: Patents per capita by decade (centred around year t), by English county, expressed as percentage of London patents per capita each decade.

County	1761	1771	1781	1791	1801	1811	1821	1831	1841	1851
BEDFORDSHIRE	0.0	25.4	0.0	5.0	3.8	14.1	10.1	0.0	4.3	2.5
BERKSHIRE	0.0	0.0	10.0	2.8	5.8	7.3	1.4	2.4	3.0	8.3
BUCKINGHAMSHIRE	0.0	4.8	0.0	5.9	2.6	2.0	9.2	4.8	4.2	11.5
CAMBRIDGESHIRE	0.0	0.0	4.3	0.0	2.8	8.1	1.7	4.3	6.3	5.1
CHESHIRE	6.1	2.9	6.3	6.8	16.0	14.1	9.2	8.0	5.8	13.2
CORNWALL	13.0	6.6	11.2	7.1	14.4	7.5	5.9	8.4	7.0	6.9
CUMBERLAND	9.7	0.0	0.0	2.8	2.2	1.6	1.4	8.7	4.3	10.9
DERBYSHIRE	7.5	15.0	13.3	8.4	17.9	11.6	22.4	11.1	9.6	15.8
DEVONSHIRE	5.6	4.8	5.3	7.4	5.9	7.6	13.4	14.4	6.1	6.6
DORSETSHIRE	0.0	0.0	0.0	8.6	4.6	1.7	3.2	0.0	1.1	0.0
DURHAM	13.3	3.6	0.0	8.3	12.7	5.9	8.6	8.4	10.9	11.2
EAST RIDING	0.0	4.0	5.8	6.5	15.9	17.8	10.1	7.6	10.5	7.8
ESSEX	0.0	6.9	3.4	4.4	10.8	13.4	12.3	13.6	10.5	14.8
GLOUCESTERSHIRE	8.0	6.4	9.3	25.4	28.7	28.4	32.1	28.5	11.7	9.4
HAMPSHIRE	4.8	0.0	12.0	7.3	15.1	6.8	8.6	14.2	6.8	10.6
HEREFORDSHIRE	10.5	11.0	4.0	6.8	0.0	0.0	0.0	0.0	3.0	6.6
HERTFORDSHIRE	0.0	4.7	0.0	3.2	9.9	14.7	4.9	17.1	7.1	7.6
HUNTINGDONSHIRE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	17.3	13.6
KENT	3.6	9.9	9.6	7.4	15.6	11.6	18.0	21.2	9.3	13.9
LANCASHIRE	17.0	11.7	18.1	11.0	15.5	11.3	17.0	20.5	26.9	33.7
LEICESTERSHIRE	0.0	0.0	6.3	5.0	9.4	8.1	4.9	13.7	27.6	19.6
LINCOLNSHIRE	0.0	2.5	1.8	3.0	4.9	0.9	5.5	5.4	3.2	7.4
LONDON	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
NORFOLK	0.0	1.8	11.1	2.3	4.7	7.9	7.7	1.6	3.8	4.9
NORTH RIDING	0.0	3.1	6.8	2.0	1.7	5.3	1.2	3.5	6.7	5.1
NORTHAMPTONSHIRE	0.0	0.0	0.0	6.9	7.9	10.5	6.8	2.4	4.4	7.7
NORTHUMBERLAND	6.4	16.7	12.3	14.9	16.5	14.6	7.2	16.9	17.4	23.3
NOTTINGHAMSHIRE	82.6	105.7	117.8	67.9	44.7	39.8	48.4	60.5	39.9	40.8
OXFORDSHIRE	9.0	0.0	13.9	11.9	9.0	6.9	3.2	6.9	15.4	5.8
RUTLAND	0.0	0.0	0.0	0.0	0.0	0.0	10.7	0.0	0.0	6.8
SHROPSHIRE	6.3	13.1	7.2	27.7	8.3	8.4	8.2	4.6	4.4	3.4
SOMERSETSHIRE	3.8	2.0	9.9	8.0	16.1	13.3	13.2	11.2	5.2	3.2
STAFFORDSHIRE	21.8	10.7	3.7	11.5	20.9	18.3	19.5	21.8	19.1	19.8
SUFFOLK	0.0	2.5	1.8	3.1	8.2	2.6	4.9	4.3	11.9	7.3
SUSSEX	0.0	0.0	0.0	11.1	4.7	8.7	14.0	3.1	4.8	6.3
WARWICKSHIRE	18.2	50.4	45.4	53.5	42.0	59.9	59.5	66.9	59.6	60.0
WEST RIDING	12.0	7.0	7.8	23.0	17.1	12.4	17.7	14.8	11.6	14.6
WESTMORLAND	0.0	0.0	0.0	7.5	0.0	0.0	0.0	3.8	1.7	11.3
WILTSHIRE	4.5	4.9	5.4	7.7	8.7	0.0	5.3	12.2	15.9	29.4
WORCESTERSHIRE	0.0	3.6	2.7	9.1	7.6	15.1	17.6	17.6	15.5	20.3

Figure 3.4: Patents per Capita by County (centred decade)

1761 **1801** **1851**



A Novel Measure of the Spatial Distribution of Technological Innovation

As a digression, I illustrate below a novel approach to mapping the spatial distribution of technological innovation with patent data, which controls for the spatial distribution of patenting itself. This is based on a case-control method influenced by the epidemiological literature on the spatial prevalence of disease. The spatial distribution of risk to a disease is estimated by how the spatial distribution of disease cases differs to that of the *population at risk*, which is estimated from a random sampling of individual addresses (see Bithell 1990,1991, Prince et al. 2001, Wheeler 2007 for examples). Analogously, by utilising a quality measure of patents, high quality patents can be used to represent cases of exceptional innovativeness while low or average quality patents can be used as controls for the underlying spatial distribution of patenting. For example, there is a differential in local innovativeness between a location with a high and low quality patent and a location with two low quality patents. The benefit of this measure is that the difference in the spatial distribution of the cases and controls represents a measure of local innovativeness while controlling for the underlying factors determining the distribution of patents such as population, industry location or individual propensity to patent.

The distributions of cases and controls can be compared using an analogous measure to the epidemiological *log relative risk density*, which identifies statistically significant differences in the distribution of the cases to the distribution of controls. This involves estimating bivariate kernel density functions for the distribution of point locations of cases and controls, and dividing case distribution by the control distribution at each point location. The result is a contour/heat map of the density of cases relative to the controls, where the x and y coordinates represent the geographical area under study and the contours/colours represent innovativeness. To carry out this methodology I follow the programming procedure in *R* proposed by Davies, Hazelton and Marshall (2011).

I take as case observations the top 10% of patents ranked by the de-trended Woodcroft citations index and their corresponding point location in ordinance survey co-ordinate units. For controls I take a random sample of observations drawn from the bottom ranked 75% patents from the same period. I use a control to case ratio of two, following Davies et al, and limit the selection of controls to the bottom 75% of the quality distribution to avoid including marginal cases among them. The distribution of cases and controls are shown in figures 3.5 and 3.6 for the periods 1750 to 1800 and 1810 to 1830, which are chosen to investigate the evolution over time[45].

Figure 3.5: High (cases) and Low (controls) Quality Patents 1750-1800

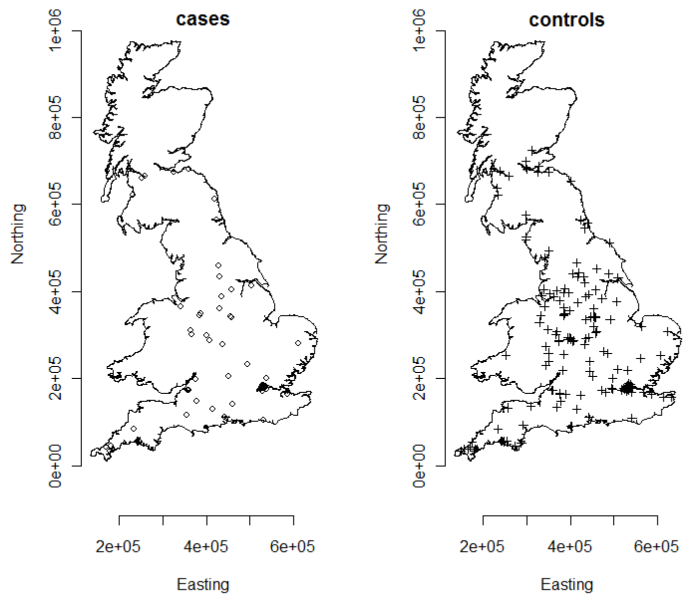
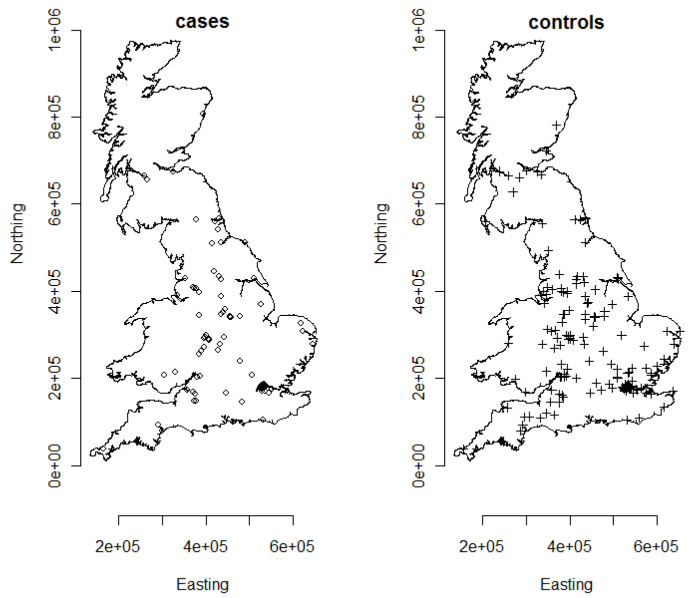


Figure 3.6: High (cases) and Low (controls) Quality Patents 1800-1830



[45] This analysis was undertaken quite early on in the PhD project. At that point I had only collected patent data up to 1830. Although I intend to do so, I have not yet extended the analysis to include the 1830-1852 patent data.

The two bivariate densities, *f* for the case observations and *g* for the controls, are estimated by kernel smoothing, using the standard bivariate normal probability density function, the Gaussian kernel:

$$\hat{f}(\boldsymbol{z}) = \frac{1}{n}\sum_{i=1}^{n} h_j^{1^{-2}} K\left(\frac{\boldsymbol{z} - \boldsymbol{X}_i^1}{h_j^1}\right)$$

and

$$\hat{g}(\boldsymbol{z}) = \frac{1}{m}\sum_{j=1}^{m} h_j^{2^{-2}} K\left(\frac{\boldsymbol{z} - \boldsymbol{X}_j^2}{h_j^2}\right)$$

where $\boldsymbol{X}_i^1$ are case observations (i = 1, … , n) and $\boldsymbol{X}_j^2$ are control observations (j = 1,…,m); *K* is the *kernel function*, chosen to be the bivariate normal probability density function (the bivariate Gaussian kernel); $\boldsymbol{z}$ is a set of two dimensional coordinate points across Britain at which *K* is evaluated, and h_j^1 and h_j^2 represent the *smoothing parameter* or *bandwidth* for the *i*th and *j*th observation of the cases and controls respectively. Often the bandwidth is chosen to be a constant value across observations, i.e. a *fixed bandwidth*. However, I follow Davies et al. in using the more flexible approach suggested by Abramson (1982) of calculating bandwidths that vary across the geographic space according to the density of observations. This enables greater local contour detail where there are more observations and less contour detail where there are fewer observations.

The estimated (*log) relative innovation density,* $\hat{r}$, can be expressed as the log ratio of the estimated case and control densities $\hat{f}$ and $\hat{g}$ respectively (the log value of the ratio is taken to symmetrize the treatment of the two densities). The estimated function $\hat{r}$ is therefore written as

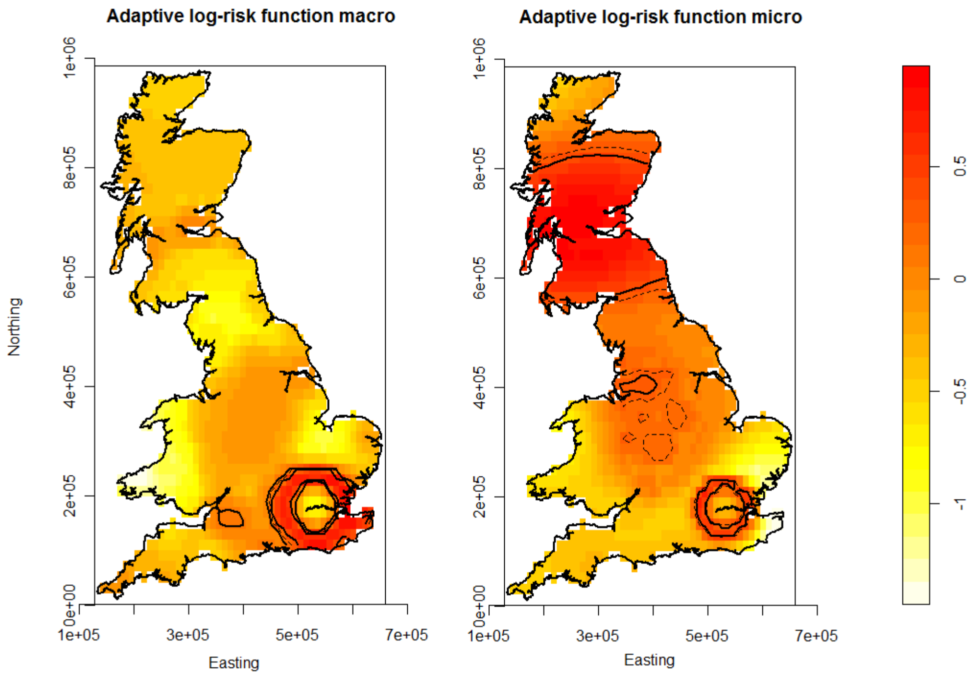
$$\hat{r}(\boldsymbol{z}) = \log\left(\frac{\hat{f}(\boldsymbol{z})}{\hat{g}(\boldsymbol{z})}\right)$$

Finally, a procedure to correct for the bias that the boundaries of the area under analysis introduce is implemented, described in Marshall and Hazelton (2010). In order to identify statistically significant fluctuations in relative innovation density, I follow a procedure described in Davies and Hazleton (2010), to test the following one-tailed hypothesis for each point-location at which $\hat{r}$ is evaluated:

$$\text{H0: } \hat{r}(\boldsymbol{z}) = 0$$
$$\text{H1: } \hat{r}(\boldsymbol{z}) > 0$$

The null hypothesis is that the relative densities of the cases and controls are not different at point *z*, and the alternative hypothesis is that the case density is higher than the control density at point *z*. This is to say that under the null hypothesis, there is no statistically significant evidence of disproportionally high innovation at a particular location, but under the alternative there *is* statistically significant evidence of an elevated innovativeness. The output of this procedure is a surface of *p*-values related to the hypothesis.

Figure 3.7: Log relative innovation density 1750-1800 (left) and 1810-1830 (right).



High innovation patent density relative to low innovation patent density. Zero signifies equal density at point location. Contour lines represent statistically significant innovativeness at the 1% level (solid line) and 5% level (dashed line).

Figure 3.7 graphically displays the results for the periods 1750-1800, and 1810-1830 respectively. Each is in the form of a heat map indicating the log relative innovation density, and contour lines representing statisitcally significant elevated innovation at the 5% (solid black line) and 10% (dashed black line) levels. It is interesting that during the second half of the eigtheenth century, London is the most innovative region. As chapter 2 showed, London dominated the KAI infrastucture during this time also. As the British Industrial Revolution progressed during the early nineteenth century, however, the midlands, northern England and Scotland become the most innovative regions. Clearly, many factors could help explain this diffusion of innovative activity, including the patterns of industrialisation taking hold. But one factor may have been the diffusion of the KAI infrastucture out of London into the provinces as illustrated in chapter 2.

KAIs and Patenting during the British Industrial Revolution: Control Variables

The patent datasets are matched with the datsets on KAIs introduced in chapter 2. For each decade centred on year *t*, extending to years *t-5* and *t+5*, the count of KAIs includes those that were present for at least one of these years. County-level counts for 1761, 1801 and 1851 are shown in table 2.3. Population is calculated by county-decade and registration district-decade and manufacturing employment by registration district-decade. Population data is taken from the decennial census covering all of Britain for 1801, 1811, 1821, 1831, 1841 and 1851. Prior to 1801, popualtion data for English counties is taken from Wrigley (2009). Scottish county popualtions prior to 1801 are estimted as follows: for 1761 I use estimates for 1755 in Webster's Analysis of Population and for 1771, 1781 and 1791, I interpolate between Webster's estimate and the 1801 census figures. Welsh county-level population data is not available at all prior to 1801, so Welsh observations only begin in 1801. Data on manufacturing employment by English registration district in 1817 and 1851 was kindly provided by the Cambridge Population Group at Cambridge University, which has constructed detailed registration district-level occupational employment datasets for these two years. The 1851 dataset is based on the 1851 census of occupations, while the 1817 dataset is the result of a 'synthetic' occupational census created by the Group (Kitson et al. 2010).

KAIs and Patenting during the British Industrial Revolution: Model

Using the panel datasets described above, I estimate the effect of KAIs on patent counts with controls. All variables are log-transformed because of their highly skewed distributions, which is typical of count data. In the case of KAIs and patents, I use the transformation *log(x+1)*, because both variables include numerous zero counts in county-decades and registration district-decades, which are too valuable to the estimation procedure to omit. A prominent prior example of this approach to dealing with zero counts is Nathan Nunn's historical study of Africa's slave trade in the *Quarterly Journal of Economics* (2008). Count data models, such as Poisson or negative binomial regression models – which can handle zero counts without the use of an arbitrary transformation – cannot be used here because of the incidental parameters problem, due to inclusion of a large set of fixed-effects (Angrist & Pischke 2009). However, the regression results displayed below are robust to altering the *log(x+1)* transformation by adding alternative arbitrary constants to the KAI and patent counts, such as 0.1 or 0.01, and indeed to excluding the zeros counts of KAIs and patents. First, I estimate the following two models:

$$LnPATENTS_{it} = \alpha + \beta_1 LnCORE\ KAIs_{it} + \beta_2 LnPUBLIC\ LIBRARIES_{it} + + \beta_3 LnMASONIC\ LODGES_{it} + \beta_4 LnBOOKSLLERS_{it} + \beta_5 LnPOP_{it} + \delta_j + \gamma_t + \varepsilon_{it} \quad (3.1)$$

$$LnPATENTS_{it} = \alpha + \beta_1 LnCORE\ KAIs_{it} + \beta_2 LnPUBLIC\ LIBRARIES_{it} + \beta_3 LnMASONIC\ LODGES + \beta_4 LnBOOKSELLERS + \beta_5 LnMALE\ POPULATION\ OVER\ 20_{it} + \beta_6 LnMANUFACRTURING\ EMPLOYMENT_{it} + \delta_j + \gamma_t + \varepsilon_{it} \quad (3.2)$$

where in equation 3.1, $LnPATENTS_{it}$ is the log of the count of patents in county *i* and decade *t*, $LnCORE\ KAIs_{it}$ is the log of core KAIs in county *i* in decade *t*, $LnPUBLIC\ LIBRARIES_{it}$ is the log of public libraries in county *i* in decade *t*, $LnMASONIC\ LODGES_{it}$ is the log of masonic lodges in county *i* in decade *t*, $LnBOOKSELLERS_{it}$ is the log of booksellers in county *i* in decade *t*, $LnPOP_{it}$ is logged population in county *i* in the centre of decade *t*. δ_j is a set of 86 county fixed effects, and γ_t is a full set of decade time fixed-effects for t = 1761, 1771, … , 1851. Standard errors are clustered by county. Some descriptive statistics for patent and KAI counts by decade are shown in table 3.3.

Equation 3.2 changes the unit of observation to 586 registration districts and time to $t = 1817$ and 1851. *LnINDUS* is the log count of manufacturing employment in registration district *i* and period *t*. Counts are *log(x+1)* transformed and standard errors are clustered by registration district.

Table 3.2: Descriptive statistics of patent and core KAI counts by decade

	Patents			Core KAIs		
Year	Mean	S.D	Max	Mean	S.D	Max
1761	1.1	2.2	13	1.6	7.4	65
1771	1.5	2.7	14	3.2	15.3	134
1781	2.0	3.4	14	4.8	21.5	187
1791	3.4	5.0	24	6.8	27.8	242
1801	4.2	6.2	33	10.0	42.0	373
1811	5.3	7.6	46	13.2	58.9	523
1821	7.8	10.0	60	16.6	70.2	619
1831	10.1	13.6	85	21.0	90.0	790
1841	14.8	21.1	122	49.9	220.4	1916
1851	19.0	27.4	171	38.4	165.5	1422

Next, I estimate the effect of KAIs on patent quality using the patent quality indicator based on the Woodcroft Reference Index. I replace the patent count in equations 3.1 and 3.2 with a count of the 10% of top patents only and add the overall patent count as a regressor, which controls for the distribution of the quantity of patenting. I estimate equations 3.3 and 3.4 below, where all subscripts have the same representation as equations 3.1 and 3.2 respectively:

$$LnTOP\ PATENTS_{it} = \alpha + \beta_1 LnCORE\ KAIs_{it} + \beta_2 LnPUBLIC\ LIBRARIES_{it} + + \beta_3 LnMASONIC\ LODGES_{it} + \beta_4 LnBOOKSLLERS_{it} + \beta_5 LnPOP_{it} + \beta_6 LnPATENTS_{it} + \delta_j + \gamma_t + \varepsilon_{it} \quad (3.3)$$

$$LnTOP\ PATENTS_{it} = \alpha + \beta_1 LnCORE\ KAIs_{it} + \beta_2 LnPUBLIC\ LIBRARIES_{it} + \beta_3 LnMASONIC\ LODGES + \beta_4 LnBOOKSELLERS + \beta_5 LnMALE\ POPULATION\ OVER\ 20_{it} + \beta_6 LnMANUFACRTURING\ EMPLOYMENT_{it} + \beta_7 LnPATENTS_{it} + \delta_j + \gamma_t + \varepsilon_{it} \quad (3.4)$$

The spatial distribution of patent quality may be influenced by industrial location if top patents are not distributed proportionally across industry sectors. If, in turn, industry sectors with high quality patents are spatially correlated with KAIs then this would bias upwards the estimate of the effect of KAIs on patent quality. Table 3.2 shows top patent ratios by sector, as measured by the proportion of sector i's patents that are top patents. Top patents were quite varied across sectors of the economy. The top sector was beverages where 14% of patents were in the top 10% by quality, second was transport with 12% and third was food at 11.1%. For industrial patents, which are most likely to be spatially correlated with KAIs, 10.5% were in the top 10%, which represents only a small skew above the unconditional expected proportion of 10%.

Table 3.2: Sector Distribution of Top Patents

Sector	**% in top 5%**	**% in top 10%**	**% in top 15%**
Agriculture	0	1.1	11.2
Beverages	9.7	14.0	19.4
Clothing	3.1	7.7	10.8
Communications	0	0	25.0
Domestic	3.1	7.7	10.4
Food	7.1	11.1	13.1
Industrial	5.2	10.5	15.2
Instruments	2.1	5.3	9.6
Medical	2.8	2.8	8.3
Military	2.4	3.6	7.2
Paper & printing	3.4	7.8	12.1
Textiles	5.6	8.9	11.2
Transport	5.5	12.0	18.3

Note: sectors not mutually exclusive.

KAIs and Patenting during the British Industrial Revolution: Results

As a starting point, figure 3.8 displays the cross-sectional relationship in 1851 between core KAIs per capita and patenting per capita, illustrating a clear correlation. Table 3.4 displays the results of the regressions based on equation 3.1. Core KAIs are strongly associated with patenting rates, both in the pooled cross-section (column 1) and within-county (column 2). Within-county, the elasticity of patenting to the growth of KAIs is 0.43 with a standard error of 0.05. Among the peripheral KAIs, Masonic Lodges appear to be associated with patenting rates, with an elasticity of 0.19 and a standard error of 0.09. Booksellers have a significant effect in the pooled cross section but not within-county and public libraries exhibit a positive but insignificant effect in both specifications. Table 3.5 displays the results of the 1817-1851 census registration districts long-panel. Core KAIs retain their strong association with patenting, both in the cross section and within-county over time. However, within-registration district the elasticity of patenting to core KAIs has roughly halved to about 0.18 with a standard error of 0.07. This might be due to correcting for manufacturing employment. Masonic lodges also retain their association with patenting, exhibiting a similar elasticity to the county level model of around 0.16 with a standard error of 0.08. Figure 3.9 shows the relationship across census registration districts of the change in KAIs between 1817 and 1851 and the corresponding change in the patent count, which has an R^2 of 0.24.

The above results indicate a significant association between the regional emergence of KAIs and patenting, suggesting a positive effect of KAIs on innovative effort as predicted by the Romer-Mokyr model. Table 3.6 presents estimates of the effect of KAIs on research productivity as captured by patent quality, based on equations 3.3 and 3.4. At the county level, there is a strong positive association between core KAIs and the quality of patenting. Top patents exhibit an elasticity of 0.24 to core KAIs with a standard error of 0.05 after controlling for the overall patent count. The impact of Masonic lodges on patent quality is negative. At the registration district level, controlling for manufacturing employment, the effect of core KAIs on patent quality is diminished, although still detectable and significant under some specifications. The elasticity of top patents to core KAIs is 0.1 in the cross section (standard error 0.03) and 0.05 within-registration district between 1817 and 1851 (standard error 0.03) if the peripheral KAIs are excluded from the model (column 3). However, when peripheral KAIs are included (column 2) the elasticity of top patents to core KAIs falls to 0.035 and is insignificant.

The main result of this study is the association of core KAIs with both patent quality and patent quantity, as the Romer-Mokyr model predicts.

Figure 3.8: Log Patents per Capita versus Log Core KAIs per Capita in 1851, by County

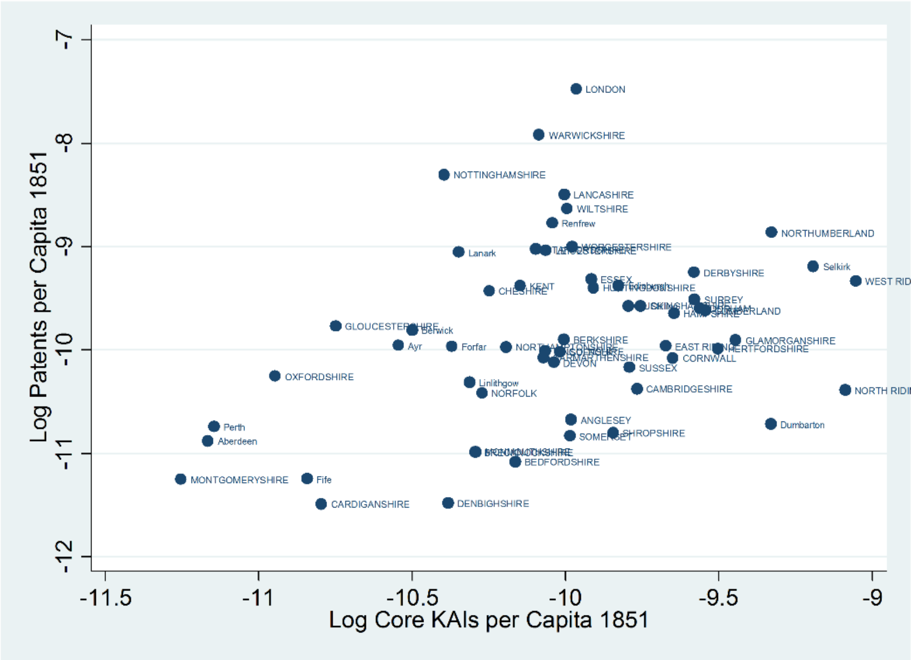


Figure 3.9: Change in log of Learned Societies vs change in log of patents, 1817 to 1851, by English census registration district

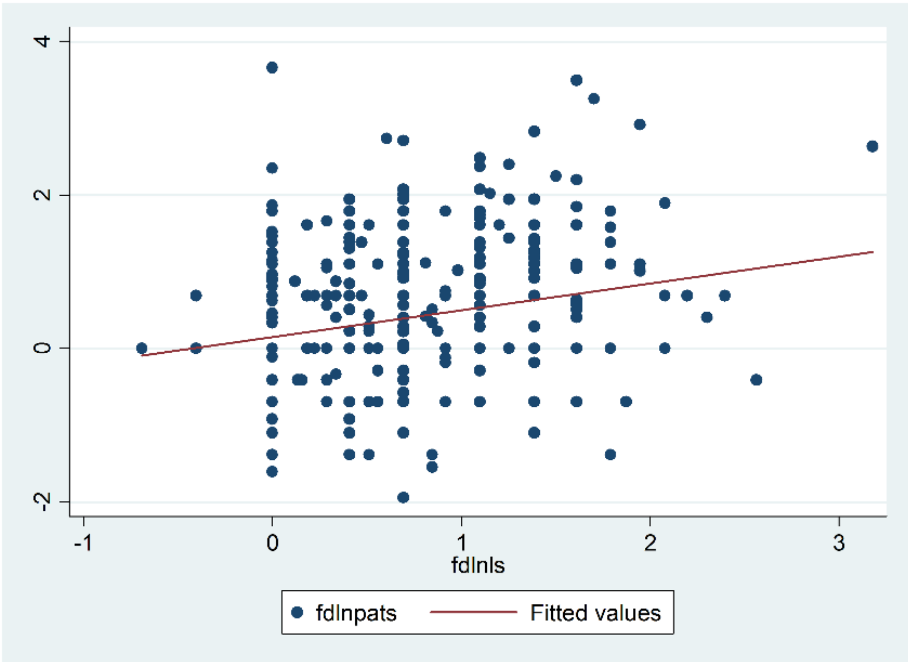


Table 3.4: Determinants of patenting by British county-decade, 1761-1851

	(1)	(2)
Data:	County-decade panel 1761-1851 *Pooled Cross Section*	County-decade panel 1761-1851 *Fixed Effects*
Dep Variable:	*Ln Patents*	*Ln Patents*
Ln Core KAIs	0.555***	0.431***
	(0.0802)	(0.0480)
Ln Public Libraries	0.0385	0.106
	(0.0556)	(0.0735)
Ln Booksellers	0.125**	0.0102
	(0.0570)	(0.0513)
Ln Masonic Lodges	0.129	0.190**
	(0.0891)	(0.0884)
Ln Population	0.323***	0.128
	(0.0760)	(0.129)
County Fixed Effects	No	Yes
Decade Fixed Effects	Yes	Yes
Observations	808	808
Counties	*86*	*86*
Years	*10*	*10*
R^2	0.755	0.633

Robust (clustered) standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.0$
Welsh counties only included from 1801 onwards due to availability of population data.

Table 3.5: Determinants of patenting by English Registration District, 1817 and 1851

	(1)	(2)
Data:	Registration District Long panel 1817 & 1851 *Pooled Cross Section*	Registration District Long panel 1817 & 1851 *Fixed Effects*
Dep Variable:	*Ln Patents*	*Ln Patents*
Ln Core KAIs	0.369***	0.184**
	(0.0590)	(0.0715)
Ln Public Libraries	0.0245	0.152
	(0.0299)	(0.0983)
Ln Booksellers	0.0197	-0.0684
	(0.0309)	(0.0442)
Ln Masonic Lodges	0.224***	0.157**
	(0.0523)	(0.0790)
Ln Population	0.188	0.973***
	(0.124)	(0.262)
Ln Manufacturing Employment	0.220***	-0.379**
	(0.0848)	(0.176)
Reg. District Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	1,175	1,175
Registration Districts	*586*	*586*
Years	*2*	*2*
R^2	0.494	0.251

Clustered robust standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
London census registration districts grouped together

Table 3.6: Determinants of patent quality by British counties, 1761 to 1851

	(1)	(2)
Data:	County-decade panel 1761-1851 *Pooled Cross Section*	County-decade panel 1761-1851 *Fixed Effects*
Dep Variable:	*Ln Top Patents*	*Ln Top Patents*
Ln Core KAIs	0.208***	0.239***
	(0.0433)	(0.0448)
Ln Public Libraries	-0.0780***	-0.0734*
	(0.0291)	(0.0436)
Ln Booksellers	0.0121	0.0303
	(0.0266)	(0.0418)
Ln Masonic Lodges	-0.00537	-0.145**
	(0.0335)	(0.0730)
Ln Population	-0.0649**	0.179
	(0.0264)	(0.111)
Ln Patents	0.416***	0.293***
	(0.0474)	(0.0332)
County Fixed Effects	No	Yes
Year Fixed Effects	Yes	Yes
Observations	808	808
Counties	*86*	*86*
Years	*10*	*10*
R^2	0.702	0.523

Clustered standard errors by county in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Welsh counties only included from 1801 onwards due to availability of population data.

Table 3.7: Determinants of <u>patent quality</u> by English Registration District, 1817 and 1851

	(1)	(2)	(3)
	Registration District Long panel 1817 & 1851	Registration District Long panel 1817 & 1851	Registration District Long panel 1817 & 1851
	Pooled Cross Section	*Fixed Effects*	*Fixed Effects*
	Ln Patents	*Ln Patents*	*Ln Patents*
Ln Core KAIs	0.110***	0.0348	0.0498*
	(0.0337)	(0.0345)	(0.0302)
Ln Booksellers	-0.00134	-0.0301	
	(0.0136)	(0.0228)	
Ln Libraries	-0.0211*	0.0864*	
	(0.0124)	(0.0480)	
Ln Masonic Lodges	0.0188	-0.0112	
	(0.0326)	(0.0403)	
Ln Patents	0.254***	0.186***	0.190***
	(0.0261)	(0.0252)	(0.0247)
Ln Population	0.136	0.382***	0.405***
	(0.0874)	(0.120)	(0.126)
Ln Manufacturing Emp.	-0.0664	-0.175**	-0.172**
	(0.0598)	(0.0729)	(0.0729)
Reg. Dist. Fixed Effects	No	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
Observations	1175	1175	1175
R^2	0.539	0.338	0.329

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Study 2: KAIs and the Great Exhibition of 1851

A shortcoming of study one is that it is short on controls. Furthermore, patenting offers only a partial perspective on technological innovation. The rich data available for the year 1851 enables a more detailed cross-sectional study based on non-patent data. Below, I use data on the addresses of the British exhibitors and prize winners at the Great Exhibition of 1851 as a proxy for the spatial distribution of innovation, detailed data on core KAIs in 1851 based on a survey of learned societies and mechanics institutes carried out in the 1851 education census and extensive data on controls based on the 1851 census.

KAIs and the Great Exhibition of 1851: Data and Model

The Great Exhibition of 1851 was a major exhibition of world technology and industry held in Hyde Park in London. Between its opening day on 1st May and final day on 11th October, the exhibition was visited by around six million people, equivalent to about a third of the British population. It showcased technological and industrial exhibits from around the world, however, about half of the exhibitors – approximately 6,400 – were British. In turn, these were chosen from around 8,200 British applicants, who submitted applications to 330 purposely-formed regional committees located throughout the country during the year prior to the exhibition. Of those admitted to the exhibition, 30 per cent were awarded prizes for a combination of the utility and novelty of their exhibit. Data on the addresses of all exhibitors and prize-winners, which is available in the exhibition's catalogue, can be used to construct a quality-filtered indicator of technological innovation across Britain in 1851. Using this data, I produce exhibit and prize counts for the 656 census registration districts covering Britain.

The British education census of 1851 included a comprehensive survey of learned and scientific societies and mechanics institutes, providing details on membership, subscription fees, frequency of meetings and subject coverage for each organisation. I distinguish core KAIs from other organisations in this survey based on the criteria set out in chapter 2 and enter the KAI-level data into a spreadsheet. Then I aggregate variables by registration district.

As a first pass at investigating the spatial relationship between core KAI membership and technological innovation, figure 3.10 shows core KAI membership and exhibits at the

Great Exhibition by registration district, both in per capita terms. The two spatial distributions share some common patterns. Figure 3.11 shows a log-log scatter plot of core KAIs versus exhibits, which has an R^2 of 0.56 and figure 3.12 shows a log-log plot in per capita terms, which has an R^2 of 0.3. The task at hand is to quantify this relationship while controlling for confounding factors.

Figure 3.10: Core KAI membership per capita (left) and Exhibits at the Great Exhibition in 1851. (Black regions are higher than median, white regions lower than median)

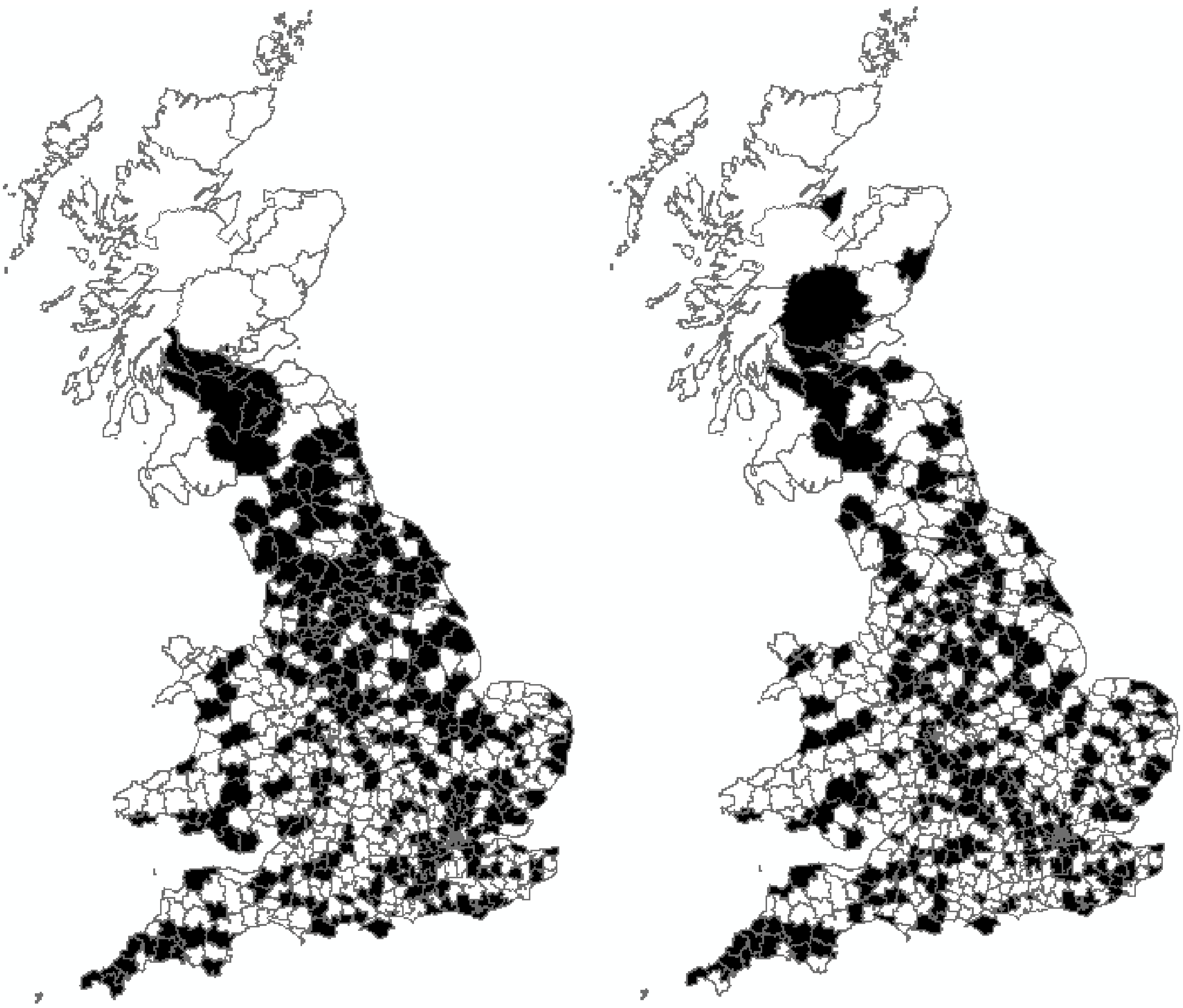


Figure 3.11: Scatterplot of log of KAI members in 1851 against log of 1851 Great Exhibition exhibitors, by British census registration district

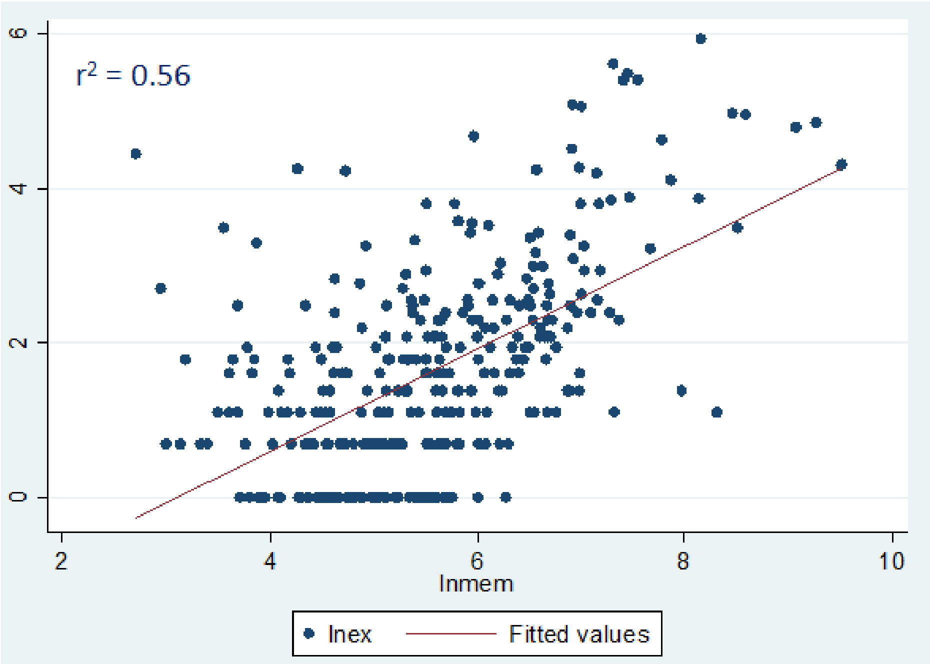
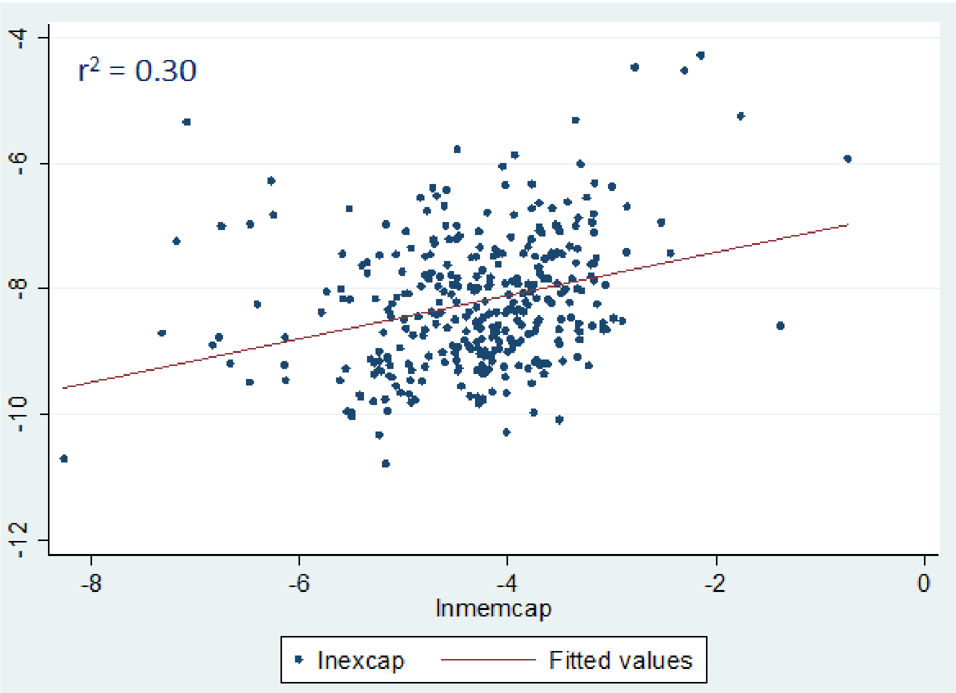


Figure 3.12: Scatterplot of log of KAI members per capita in 1851 against log of 1851 Great Exhibition exhibitors per capita, by British census registration district



To control for the location of industrial production, which may be correlated both with technological innovation and core KAI membership, first I stratify the innovation counts across 10 industrial sectors, producing counts of exhibits and prizes for 6,560 industry-regions. Then, I calculate the size of the labour force employed in the secondary sector in each of the 10 industries in each registration district, using occupational data from the 1851 census provided by the Cambridge Population Group. This enables me to produce within–industry sector estimates of the effects of the covariates, while controlling for the location of specific industrial activity. Table 3 displays descriptive statistics for each of the industry sector exhibitor and prize winner counts.

To control for other factors that may affect both core KAI members and technological innovations, I include population density and a proxy for the regional literacy rate derived from the proportion of grooms by registration district who signed their name on the marriage register in 1851, as recorded by the Registrar General (Annual Report of the Registrar General 1852). I include the size of the adult population in each registration district and a dummy for London registration districts to control for possible idiosyncrasies of the capital.

Table 3.8: Great Exhibition exhibit and prize counts by registration district, by industry

Industry	Count of exhibits per census reg. district			Count of prize winners per census reg. district		
	Mean	Max	S.D.	Mean	Max	S.D.
Mining and metallurgy	0.48	15	1.42	0.08	4	0.34
Chemicals	0.19	10	0.88	0.09	6	0.52
Food processing	0.19	7	0.67	0.08	5	0.39
Manufactures	4.47	215	17.53	1.47	93	6.71
Engines	0.56	31	2.21	0.1	8	0.57
Manufacturing machinery	0.34	26	1.49	0.09	12	0.63
Civil, mil, naval engineering	0.72	29	2.65	0.09	6	0.5
Agricultural machinery	0.36	9	0.96	0.04	2	0.21
Instruments	0.83	39	3.39	0.2	16	1.18
Textiles	0.82	51	4.12	0.24	19	1.43

The process for recruiting exhibitors could in principle influence the correlation between KAIs and exhibitors for various reasons. If core KAI membership gave prospective exhibitors an advantage other than better capabilities for technological innovation, such as enhanced awareness of the exhibition or benefits of favouritism, then this might bias upwards estimates of the impact of KAIs on technological innovation. The 330 local committees operated out of the offices of the respective town mayors. Core KAIs were not a formal contact point. Indeed, some committees treated mechanics institutes with suspicion because of their reputation for harbouring radical political views, worrying that mechanics institutes might attempt to sabotage the exhibition (Davis 1999). Although the public's awareness of the exhibition may have been enhanced by KAIs, it was extremely high anyway, as Davis describes (Davis 1999), so the marginal impact of core KAIs would have been small. The call for exhibitors was advertised extensively via a national campaign covered by the local and national media. Moreover, news coverage began as early as June 1849 and, following the establishment of a Royal Commission led by Prince Albert on 3rd January 1850, hundreds of delegations and tens of thousands of letters were sent out into the provinces to raise awareness. Prince Albert's involvement lent the exhibition star power, but perhaps the greatest stimulus for public attention was frequent controversy fuelled by public relations disasters related to the proper role of state financing, protectionist concerns about revealing British technology to foreigners, the harmful effect of the exhibition building on Hyde Park and the danger posed by hordes of 'marauding northerners' descending on London. Each of these issues were debated in parliament and the media (Davis 1999).

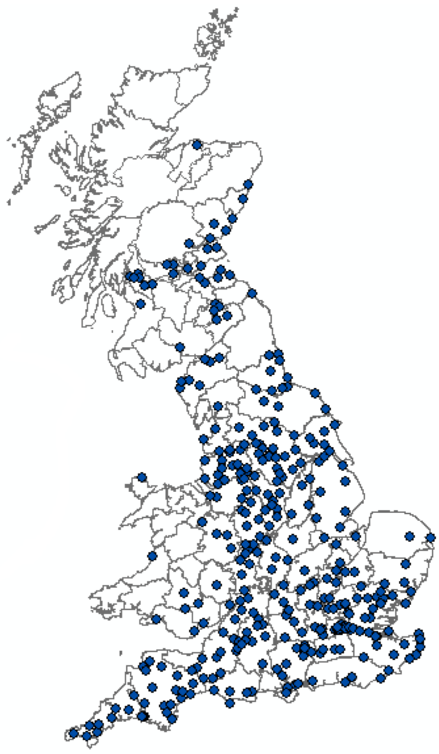
Data on the location of the 330 local committees is available in the official report on the exhibition. I use it to control for the presence of a local committee by registration district. The geographic distribution of local committees is shown in figure 3.13. A second potential problem is that central organisers might have wished to achieve a balanced distribution of exhibitors across local committees. However, this does not appear to have had a major effect, as there is very wide variation in the numbers of exhibitors by local committee.

Was exhibiting financially prohibitive for ordinary inventors? Exhibitors were not required to pay a fee to exhibit, rather the working capital for the exhibition was supplied by around £75,000 of subscriptions donated gratuitously by the public following considerable fund raising efforts[46]. Nevertheless, given that there ultimately proved to be excess exhibitor

[46] Ticket sales revenue would eventually vastly exceed expectations allowing the exhibition to turn a very large profit of £183,000, which was subsequently used to finance a set of scientific and artistic institutions near the

demand for spaces at the exhibition, subscriptions might have served, *de facto*, to buy spaces. This is not necessarily a challenge to the identification of the effect of KAIs on exhibits, nevertheless, it determines whether the process selected for wealthier innovators.

Figure 3.13: Locations of the Great Exhibition 1851 Local Committees



Did subscriptions buy exhibition spaces? The *Official Catalogue* lists total subscriptions raised and the number of exhibitors accepted by each of the 330 local committees. Under the extreme assumption that exhibitors only subscribed to buy a space at the exhibition, I derive an upper-bound estimate of the cost of an exhibit space by regressing the number of exhibitors accepted by each of the local committees on the value of subscriptions received controlling for local population based on the 1851 census. The co-efficient on subscriptions is £7.60 (with a standard error of about £1), which represents a reasonable estimate for the average cost of an exhibit space. Based on Gregory Clark’s national wage series (Clark 2011) this represents about 14% of the average annual wage in Britain in 1850. The cost of transporting an exhibit to the exhibition was not high. Train fares from northern manufacturing

site of the exhibition in South Kensington including Imperial College, the V&A Museum and the Royal Albert Hall.

towns, for example, cost between 5s and 10s and all rail companies offered a half-price concession to exhibitors (Auerbach 1999). The cost of transportation for an exhibitor amounted to about the same as the national average daily wage of around 3.3s (Clark 2011). In total, these costs do not appear prohibitive to the average inventor relative to the prospective benefit of accessing the large potential market at the exhibition and the possibility of receiving an award from the exhibition's £20,000 prize fund or a Royal medal that could enhance the reputation of one's business. Although the benefits to exhibiting and patenting are not comparable, the cost of exhibiting was certainly less financially prohibitive to budget constrained inventors than the British patent system during the Industrial Revolution. As such, it is likely that the innovators observed in this study represent a wider sample in terms of social class than those observed in the patenting study.

To estimate the effect of core KAIs on exhibits and prizes, I use the negative binomial model due to its suitability for handling a count dependent variable[47]. Since the analysis is cross-sectional with relatively few fixed-effects the incidental parameter problem does not prohibit this approach, as it does in studies one and three. This produces the following specification:

$$y_{ij}^{k} = exponential\ (\alpha + \beta_1 MEM_{ij} + \beta_2 MEM_{i-1,j} + \beta_3 EMP_{ij} + \beta_4 EMP_{i-1,j} + \beta_5 DEN_i + \beta_6 DEN_{i-1} + \beta_7 LIT_i + \beta_8 LIT_{i-1} + \beta_9 POP_i + \beta_{10} LON_i + \beta_{11} LOC\_COMM_i + \delta_j + \varepsilon_{ij}) \quad (3.5)$$

where k = 1 or 2 and y_{ij}^{1}= exhibits in region i and industry j, y_{ij}^{2} = awards in region i and industry j, MEM_{ij} = number of core KAI members in region i (/100), EMP_{ij} = employees in the secondary sector in region i and industry j (/1,000), DEN_i = population density in region i (persons per km^2), POP_i = population in region i (/10,000) , LIT_i = male literacy rate in region i, LON_i = London dummy, δ_j = industry sector fixed effect, ε_{ij} = random error, and variables with $i-1$ subscript are spatially lagged variables. I include spatial lags of regressors to allow for knowledge spillovers operating over areas larger than registration districts. For each registration district, I take the average value of each regressor in bordering registration districts.

[47] Preferred to a Poisson model owing to 'overdispersion' in the data and better model selection criteria scores.

Standard errors are clustered by registration district to allow for errors to be correlated within registration districts from one industry sector to the next. Second, to test for robustness, I estimate the following model, which includes the same underlying variables as 3.5, but uses simple OLS on log transformations:

$$y_{ij}^{k} = \alpha + \beta_1 MEM_{ij} + \beta_2 MEM_{i-1,j} + \beta_3 EMP_{ij} + \beta_4 EMP_{i-1,j} + \beta_5 DEN_i + \beta_6 DEN_{i-1} + \beta_7 LIT_i + \beta_8 LIT_{i-1} + \beta_9 POP_i + \beta_{10} LON_i + \beta_{11} LOC\_COMM_i + \delta_j + \varepsilon_{ij} \quad (3.6)$$

In addition to the main specifications, I stratify KAI membership by the three types of core KAI introduced in chapter 2: learned societies, professional societies and mechanics institutes to examine their distinct impact. Figure 3.11 displays KAI members per capita and exhibitors per capita by registration district.

KAIs and the Great Exhibition of 1851: Results

There is strong evidence of an impact of KAIs on local technological innovation. Coefficients in table 3.9 are reported as semi-elasticities, so the first column tells us that an extra 100 core KAI members in a registration district was associated with a 5.6 per cent rise in exhibits and a 6.4 per cent rise in prizes in this registration district. Bear in mind that the overall exhibition floor space available to British exhibitors was fixed and oversubscribed so general equilibrium considerations means that this result represents a 5.6% and 6.4% rise in registration district *i relative to the other registration districts.* The standard deviation of core KAI membership in a registration district was 746, so this suggests that a one standard deviation rise in core KAI members was associated with an economically significant 42 per cent relative rise in exhibits (7.46 x 5.6 per cent) and 48 per cent relative rise in prizes (7.46 x 6.4 per cent). Coefficients on core KAI membership across the four regressions are highly statistically significant. They are also highly robust to controlling for spillovers from neighbouring districts, falling only from 5.6 to 5.4 per cent for exhibits and from 6.4 to 6.1 per cent for prizes. Coefficients on non-spatial lag controls are mostly of expected sign and statistically significant.

Table 3.9: Determinants of Exhibitors and Prize Winners at the Great Exhibition of 1851, by Industry Sector-British Census Registration District, Negative-Binomial Model

	Count Model (Neg. Binomial)	*Count Model (Neg. Binomial)*	*Count Model (Neg. Binomial)*	*Count Model (Neg. Binomial)*
Dependent Var:	Exhibits in Sector j	Exhibits in Sector j	Prizes in Sector j	Prizes in Sector j
Spatial lag	*No*	*Yes*	*No*	*Yes*
MEM_{ij}	.056***	.054***	.064***	.061***
(100 mem)	(3.96)	(3.73)	(4.16)	(3.70)
EMP_{ij}	.062***	.054**	.069***	.064***
(1,000 emp)	(3.40)	(2.44)	(3.72)	(2.78)
DEN_i	.049***	.060***	.061***	.063**
(1000 cap per km^2)	(3.60)	(2.71)	(3.54)	(2.34)
POP_i	.32	.37	.56	.14
(10,000 cap)	(0.78)	(0.86)	(0.12)	(0.28)
LIT_i	.020***	.021***	.011*	.012*
(%)	(4.63)	(4.89)	(1.66)	(1.86)
LOC_COMM_i	.61***	.61***	.59***	.59***
(binary)	(7.14)	(7.15)	(5.88)	(5.73)
$MEM_{i-1,j}$		-.016*		-.018
(100 mem)		(-1.71)		(-1.27)
$EMP_{i-1,j}$		.030		.025
(1,000 emp)		(1.27)		(0.75)
DEN_{i-1j}		-.085		0.023
(1000 cap per km^2)		(-0.04)		(0.89)
Industry Fixed Effects	Yes	Yes	Yes	Yes
N	6,520	6,430	6,520	6,430
Pseudo R^2	0.18	0.18	0.21	0.21

Robust registration district clustered t-stats in brackets, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.10: Determinants of Exhibitors and Prize Winners by British Census Registration District at the Great Exhibition of 1851, OLS Estimation

	OLS	*OLS*	*OLS*	*OLS*
Dependent Var:	Ln Exhibits in Sector j	Ln Exhibits in Sector j	Ln Exhibits in Sector j	Ln Exhibits in Sector j
Spatial lag	*No*	*Yes*	*No*	*Yes*
Ln KAI Members$_i$	0.0105**	0.00942*	0.00631**	0.00580**
	(0.00474)	(0.00481)	(0.00279)	(0.00287)
Ln Sector Employment$_{ij}$	0.0495***	0.0408***	0.0239***	0.0199***
	(0.00766)	(0.00878)	(0.00470)	(0.00485)
Ln Density$_i$	0.0815***	0.104***	0.0477***	0.0572***
	(0.0151)	(0.0178)	(0.00929)	(0.0114)
Ln Population$_i$	0.0669**	0.0638**	0.0186	0.0129
	(0.0289)	(0.0309)	(0.0161)	(0.0180)
Ln Literacy$_i$	0.170***	0.158***	0.0389*	0.0295
	(0.0419)	(0.0439)	(0.0215)	(0.0218)
Local Committee$_i$	0.0464**	0.0395**	0.00819	0.00589
	(0.0190)	(0.0199)	(0.0127)	(0.0133)
London Dummy	0.523***	0.605***	0.191**	0.212**
	(0.129)	(0.128)	(0.0872)	(0.0823)
Ln Lagged KAI Mems$_i$		0.0121		0.0110
		(0.0104)		(0.00665)
Ln Lagged Sec Emp$_i$		0.0189*		0.00822
		(0.0107)		(0.00618)
Ln Lagged Density$_i$		-0.0435***		-0.0166*
		(0.0149)		(0.00875)
Sector Fixed Effects	Yes	Yes	Yes	Yes
Observations	5621	5536	5621	5536
R^2	0.412	0.416	0.255	0.257

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.11: Great Exhibition Analysis, results by type of Core KAI

Dependent Variable	Type of KAI	Co-efficient (semi-elasticity)	*P*-value
Exhibits	*Learned Societies*	0.09	0.16
	Professional Societies	-0.05*	0.09
	Mechanics Institutes	0.08***	0.00
Prizes	*Learned Societies*	0.1*	0.084
	Professional Societies	-0.04**	0.029
	Mechanics Institutes	0.08***	0.000

*All other covariates and specification the same as regression in table X, without spatial lags

Table 3.10 reports the results of re-estimating the relationships above using OLS with logged variables instead of count data models. The results are highly robust to this alternative approach. Both exhibit and prize counts remain responsive to core KAI membership and statistically significant, with and without spatial lags. Table 3.11 reports coefficients from count data models (semi-elasticities) and corresponding *p*-values when core KAI membership counts by registration district are stratified by the three types of core KAI defined in chapter 2, and included together in the same regression. The other covariates included are the same as the baseline specifications (without spatial lags) and are not reported here. The effect on both exhibits and prizes appears to be due to generalist learned societies and mechanics institutes. Professional societies are associated with significantly fewer technological innovations. Although speculative, this may be due to the rent-seeking tendencies of professional societies noted in chapter 2. Professional societies may have provided a less conducive environment for the sharing of innovative knowledge given the high degree of product market competition between members, a la Katz (1984) and they may have resisted technological innovation to protect the mutual rents of members.

Study 3: US Agricultural KAIs and Agricultural Patents

The previous two studies examined the link between KAIs and the British Industrial Revolution. But KAIs were not limited to Britain, nor were their activities limited to the industrial sector of the economy. In *Agricultural Enlightenment: Knowledge, Technology, and Nature, 1750-1840*, Peter M. Jones argues that an 'Agricultural Enlightenment' ran alongside the Industrial Enlightenment. He documents the accelerating flows of useful knowledge between British farmers during the century of the British Industrial Revolution and the role played in this process by agricultural KAIs such as agricultural societies and farmer's clubs (Jones 2016). Systematic data on agricultural KAIs in Britain in the eighteenth and nineteenth centuries is difficult to obtain but rich data is available on the contemporaneous growth of agricultural KAIs in the United States. This data can be used along with data from the decennial US agricultural censuses as the basis of a third test of the impact of KAIs on technological innovation, while retaining the context of an economy experiencing the onset of modern economic growth.

The United States developed a substantial infrastructure of core KAIs during the nineteenth century. This followed modest progress in the eighteenth century, the highlight of which was the founding of the American Philosophical Society by a group of private individuals including Benjamin Franklin in 1743. American KAIs were ultimately more akin to their British than continental counterparts in the sense that they tended to be funded and run primarily by private individuals rather than by the state. Nevertheless, the US government played a more active supporting role to KAIs than the British government through the provision of significant subsidies and the establishment of co-ordinating bodies.

Although an overall survey of US core KAIs in the eighteenth and nineteenth centuries would be a useful complement to the British survey in this thesis, the current study is restricted to agricultural KAIs due to the relative ready availability of data. In any case, US agricultural KAIs happen to provide an interesting case study of government support for KAIs owing to the activities of the Patent Office and the US Department of Agriculture, offering an opportunity to contrast with the laissez-faire British case.

The first US agricultural KAI was the Philadelphia Society for Promoting Agriculture, founded in 1785. It was followed before the turn of the century by societies in Charlestown in

Southern Carolina, Boston, New Haven, Hallowell in Maine, New York City and Middlesex County in Massachusetts. The number of societies continued to grow gradually during the early nineteenth century, as figures 3.16 and 3.17 show. The articles of association of these early societies reveal that they were founded for the collection and dissemination of farming knowledge, particularly from England and other foreign countries.

Operationally, they resembled British KAIs, holding meetings, publishing transactions, housing periodicals and books and corresponding with one another – although unlike most British KAIs (with the notable exception of the Royal Society of Arts) they often awarded premiums for agricultural innovations. Numerous early societies received state aid, particularly in the states of Massachusetts and New York. From 1839, the year work began on the first agricultural census, Federal aid began to be disbursed to agricultural societies, Congress providing £1,000 annually for the national collection of agricultural information and data. In the 1850s this was increased markedly, to \$5,000 in 1851, \$35,000 in 1854 and \$105,000 in 1856. The government assisted private societies financially but also established 'state societies', which acted as central nodes in state networks. In association with these financial resources, from 1839 onwards the Patent Office released a substantive and widely read annual agricultural report, of which around 267,000 copies were issued in 1855. These commitments paved the way for the establishment of the US Department of Agriculture in 1862. Around this time, the number of agricultural KAIs in the US exploded from less than 200 in 1850 to about 1,500 in 1870 (Bidwell & Falconer 1925).

Did this mid-century explosion of US agricultural KAIs have an effect on US agricultural technology? Certainly, it was a major institutional development in terms of scale. Furthermore, as Gallman's estimates, displayed in figure 3.16, show, agricultural labour productivity growth surged post 1850, albeit interrupted during the 1860s by the Civil War (Gallman 1960).

Figure 3.14: US Agricultural Societies, Absolute and Per 100,000 Capita, 1776-1876

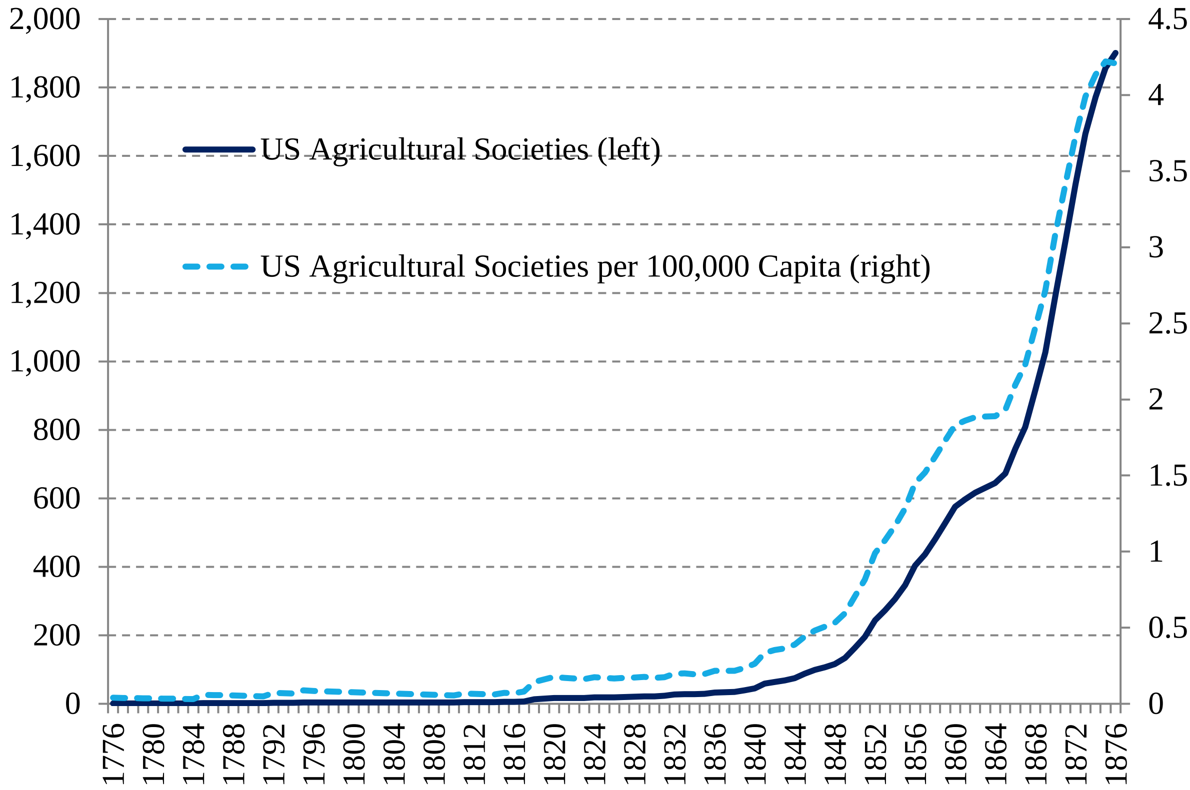


Figure 3.15: US Agricultural Societies Founded in Each Year, 1785-1876

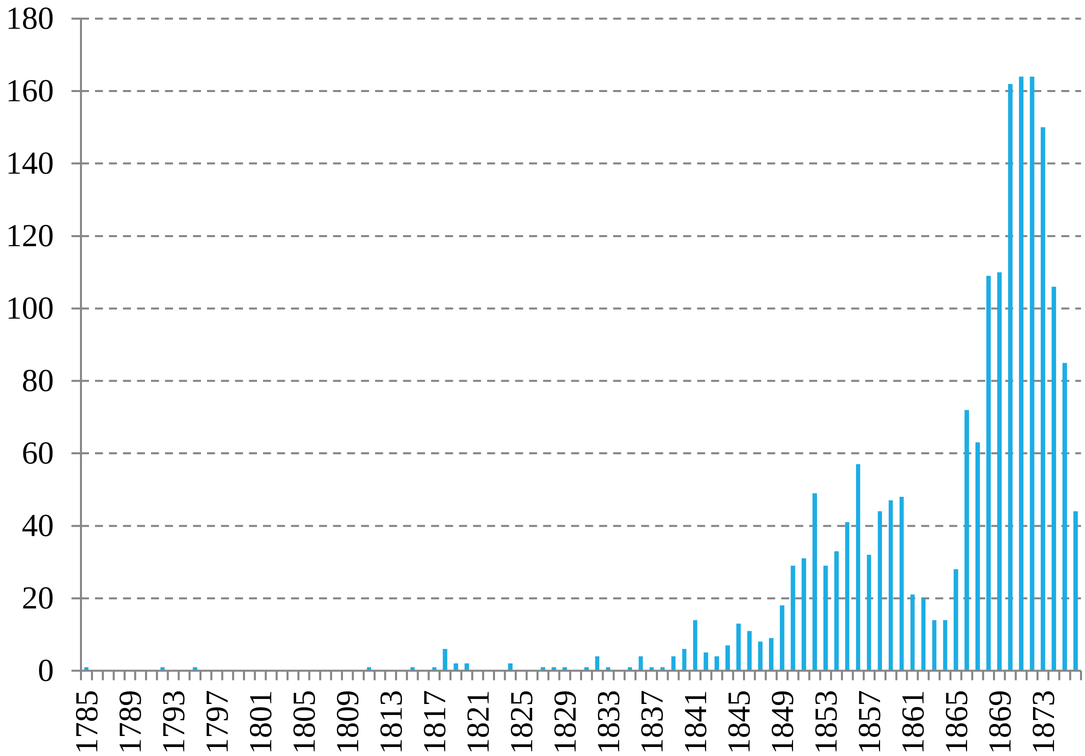
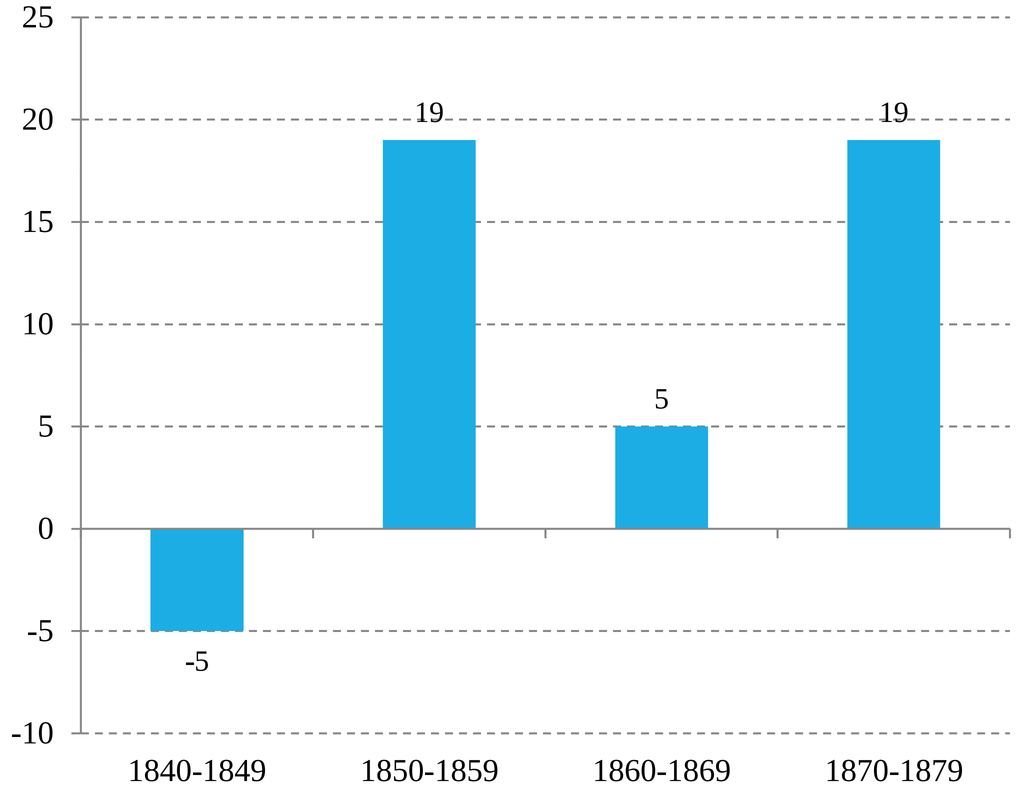


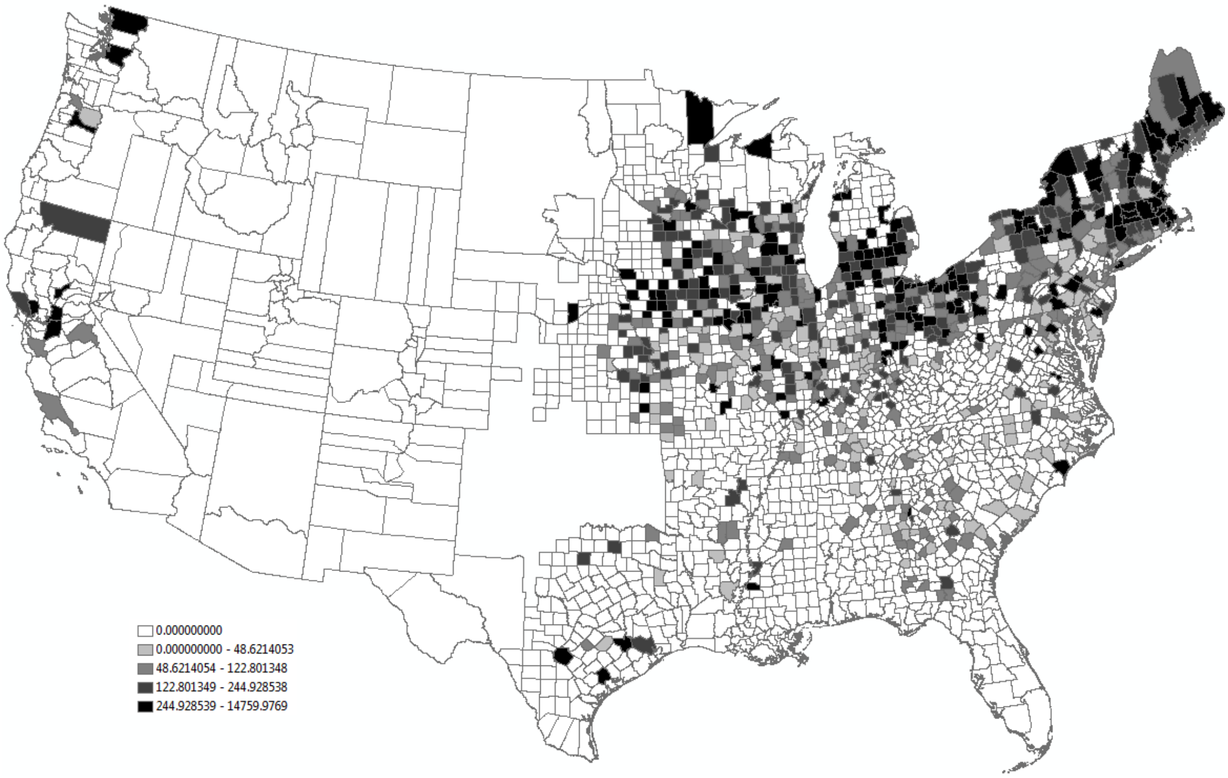
Figure 3.16: Decennial % Growth in US Agricultural Value Added Per Gainful Worker (Gallman 1960)



US Agricultural KAIs and Patents: Data and Model

In 1876 the US Department of Agriculture published *A List of Agricultural Societies and Farmers Clubs established to promote the Agricultural, Horticultural and Pomological Interests of the Farmer on the Books of the Department of Agriculture*, which provides rich data on the first century or so of US agricultural societies (US Department of Agriculture 1876). For each society, it provides details on location, date of foundation, number of members in 1876, whether it was a operated by the state or not, whether it corresponded with the state society, number of meetings held per year and whether it held annual agricultural fairs or not. I manually enter the data from this survey into a spreadsheet and use a GIS programme to geocode based on the location field. Then, I construct a county-year panel of agricultural KAIs for years 1840, 1850, 1860 and 1870, to match the years of the agricultural and general censuses. Figure 3.17 shows a map of the distribution of agricultural KAIs per capita by county in 1870.

Figure 3.17: US Agricultural Society Members per 10,000 Rural Population in 1870



Next, I construct agricultural patent counts by county-decade as follows. First, I access the database of all US utility patents filed between 1790 and 1873 located at the Patent and Trademark Resource Centre Association (PTRCA 2013). The original source for this database is the *Subject Matter Index of Patents for Inventions by the United States Patent Office from 1790 to 1873 Inclusive* (USPO 1873). Then, using GIS programming, I geocode the residence of the first patentee for each patent and assign to county and state. Next, I classify each patent by 'technology class' by cross referencing with the technology classification database at the US Patent and Trademark Office, which provides one or more of around 450 technology classes (e.g. 'plant husbandry' or 'electrical resistors') for every patent registered (see USPTO 2013 for the database interface and USPTO 2012 for a manual on the classification system). I identify all agricultural patents in this database by matching with the following fourteen patent classes: Plant husbandry, Harness for working animal, Harvesters, Chemistry: fertilizers, Planting, Animal husbandry, Wells, Unearthing plants or buried objects, Earth working, Boring or penetrating the earth, Fences, Closure fasteners, Hydraulic and earth engineering, and Crop threshing or separating. Table 3.12 show the counts for each agricultural technology class. There are 24,468 agricultural patents in total.

Figure 3.18: US Agricultural Patents, 1790-1873

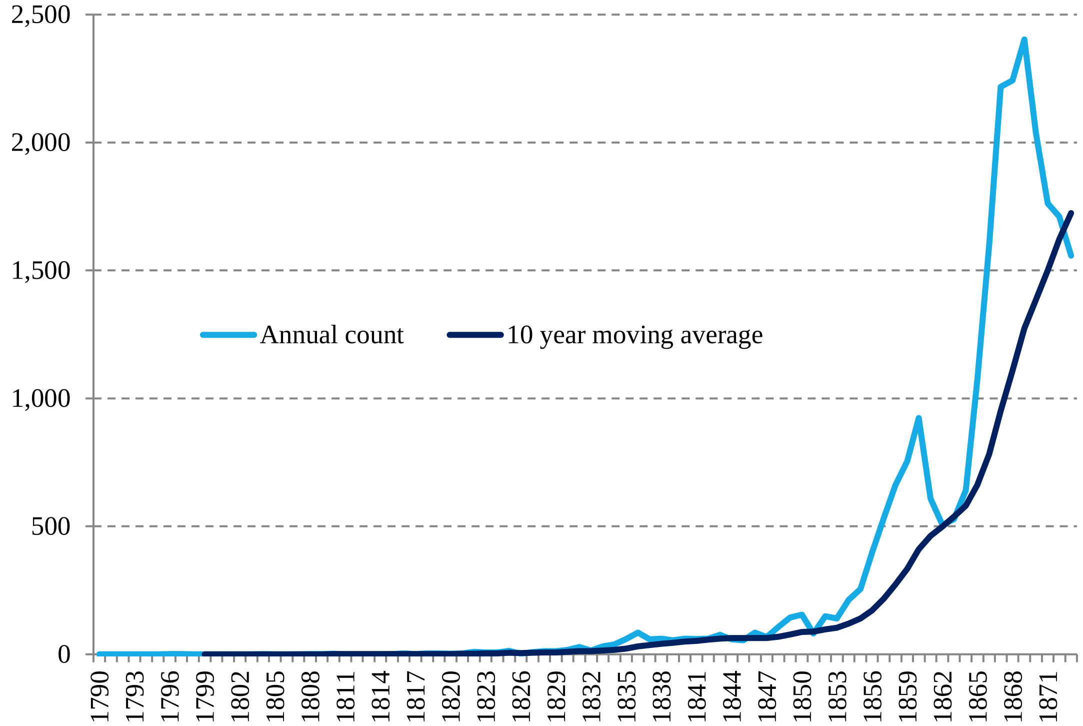


Table 3.12: US Agricultural Patent Classes and Counts

Class	Class Description	Count
47	Plant husbandry	381
54	Harness for working animal	1,765
56	Harvesters	4,057
71	Chemistry: fertilizers	574
111	Planting	2,385
119	Animal husbandry	1,004
166	Wells	317
171	Unearthing plants or buried objects	842
172	Earth working	6,749
175	Boring or penetrating the earth	826
256	Fences	1,086
292	Closure fasteners	2,474
405	Hydraulic and earth engineering	445
460	Crop threshing or separating	1,563

Finally, I construct a panel of control variables for the agricultural sector using agricultural and general census data from version 11 of the NHGIS database (NHGIS 2011). These variables are agricultural output, population, the ratio of city dwellers to the overall population and the ratio of town dwellers to overall population for county *i* and census year *t*. I estimate the following model within-county using OLS:

$$LnAGRICULTURAL\_PATENTS_{it} = \alpha + \beta_1 LnAGRICULTURAL\_SOCIETIES_{it} + \beta_2 LnNON\text{-}AGRICULTURAL\_PATENTS_{it} + \beta_3 AGRICULTURAL\ OUTPUT_{it} + \beta_4 LnPOP_{it} + \beta_5 CITY\ RATIO_{it} + \beta_6 TOWN\ RATIO_{it} + \delta_i + \gamma_t + \varepsilon_{it} \qquad (3.7)$$

using a *ln(x+1)* transformation for agricultural patent counts. *NON-AGRICULTURAL PATENTS* represent counts in county *i* and year *t* of all patents not included in the fourteen agricultural classifications, δ_i is a set of county fixed effects, and γ_t is a full set of time fixed effects for t = 1840, 1850, 1860 and 1870. Standard errors are clustered by county. To explore the influence of the activities of agricultural KAIs, I estimate models of the same basic form with the same controls, but replace the county-level counts of agricultural KAIs with counts of meetings per year and agricultural fairs. Finally, I substitute in counts of agricultural KAIs by a dummy for the corresponding status of each KAI with the state. Table 3.13 provides descriptive statistics for the overall panel dataset constructed for the study.

US Agricultural KAIs and Patents: Results

Table 3.14 displays the results of equation 3.7 estimated using a pooled cross-section with time fixed-effects and using county and time fixed-effects. In both cases I report specifications controlling for and not controlling for non-agricultural patent counts. Agricultural patents are strongly associated with the presence of agricultural KAIs. Before controlling for non-agricultural patents, the elasticity of agricultural patenting to agricultural KAIs is about 0.3 with a standard error of about 0.03. After controlling for non-agricultural patents these elasticities fall to 0.12 in the cross-section and 0.15 within-county over time, remaining statistically significant with a standard error of about 0.02.

Table 3.15 displays the results of replacing agricultural KAI counts be county year with counts of agricultural meetings and fairs per year. The count of meetings is not significantly related to agricultural patenting rates but the prevalence of agricultural fairs is significant determinant of agricultural patenting in each specification. This result fits with the intended role of agricultural fairs as technological exhibitions. Table 3.16 stratifies KAI counts by type of society – state, state correspondent and non-state correspondent. Interestingly, the overall effect of agricultural KAIs on agricultural patenting appears to be via agricultural KAIs that corresponded with state societies, not the state societies themselves nor the societies that did not correspond. Speculatively, the undetected effect of state KAIs might point towards the superiority of the private sector orientation of KAIs, as in the British as opposed to the continental case. At the same time, the most effective US agricultural KAIs were the ones that were plugged into the state's network of information and subsidies. Perhaps Britain's KAIs could have been enhanced by government support.

Conclusion

By exploiting three different datasets, the studies in this chapter provide complementary results that support the argument that core KAIs facilitated technological innovation during the emergence of modern economic growth. Nevertheless, although they illustrate a correlation between KAIs and technological innovation they do not prove causation. Were KAIs an exogenous cause of the British Industrial Revolution or were they merely a product of it? In the next chapter I turn to this question.

Table 3.13: Descriptive Statistics of Agricultural Patents and Agricultural Societies by County-Year, 1840-1870

	Year	1840	1850	1860	1870
Agricultural Patents	*Mean*	0.030	0.062	0.306	0.625
	S.D.	0.006	0.009	0.024	0.042
Non-Agricultural Patents	*Mean*	0.272	0.448	1.712	4.447
	S.D.	0.049	0.081	0.292	0.651
Agricultural Societies	*Mean*	0.035	0.100	0.273	0.507
	S.D.	0.006	0.009	0.015	0.020
Ag. Society Members	*Mean*	21.192	58.793	122.034	144.425
	S.D.	4.505	7.055	9.592	9.636
Ag. Society Meetings Per Year	*Mean*	-	-	-	3.924
	S.D.	-	-	-	0.217
Ag. Society Fairs Per Year	*Mean*	-	-	-	0.391
	S.D.	-	-	-	0.017
State Ag. Societies	*Mean*	-	-	-	0.019
	S.D.	-	-	-	0.004
Corresponding Ag. Societies	*Mean*	-	-	-	0.312
	S.D.	-	-	-	0.015
Non-Corresponding Ag. Societies	*Mean*	-	-	-	0.157
	S.D.	-	-	-	0.010
Agricultural Output	*Mean*	578,838	658,424	795,343	1,068,735
	S.D.	18,692	17,616	18,715	25,605
Population	*Mean*	13,339	14,354	15,009	16,837
	S.D.	493	576	631	732
City Ratio	*Mean*	0.005	0.009	0.009	0.012
	S.D.	0.0017	0.0019	0.0018	0.0019
Town Ratio	*Mean*	0.022	0.028	0.036	0.061
	S.D.	0.0027	0.0025	0.0025	0.0067

Table 3.14: Determinants of US Agricultural Patents by County-Year, 1840-1870 (10 yearly)

	(1)	(2)	(3)	(4)
	Agricultural Patents *County Pooled 1840-1870*	Agricultural Patents *County Pooled 1840-1870*	Agricultural Patents *County FE 1840-1870*	Agricultural Patents *County FE 1840-1870*
Agricultural KAIs	0.326***	0.119***	0.306***	0.158***
	(0.0220)	(0.0198)	(0.0276)	(0.0248)
Non-Agricultural Patents		0.275***		0.261***
		(0.0123)		(0.0155)
Agricultural Output	-0.00362*	0.00635***	-0.00189	-0.000649
	(0.00213)	(0.00154)	(0.00358)	(0.00301)
Population	0.0598***	0.00461	0.00561	0.000600
	(0.00623)	(0.00343)	(0.0127)	(0.0103)
% of Pop in Cities	1.226***	0.399***	1.675***	0.710***
	(0.152)	(0.110)	(0.268)	(0.194)
% of Pop in Towns	0.141	0.00523	0.775***	0.307**
	(0.0903)	(0.0130)	(0.253)	(0.123)
County Fixed Effects	No	No	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	7,257	7,257	7,257	7,257
Years	4	4	4	4
R^2	0.341	0.470	0.247	0.368

Robust standard errors, clustered by county, in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.15: US Agricultural Patents by County and Activities of Agricultural Societies Therein, 1873

	(1)	(2)	(3)	(4)
	Agricultural Patents *OLS (in logs) Cross Section 1873*	Agricultural Patents *OLS (in logs) Cross Section 1873*	Agricultural Patents *Negative Binomial Cross Section 1873*	Agricultural Patents *Negative Binomial Cross Section 1873*
Meetings per year	0.00917	0.00454	0.00458	0.00458
	(0.0121)	(0.0111)	(0.00385)	(0.00386)
Agricultural Fair	0.194***	0.0689*	0.149**	0.148**
	(0.0398)	(0.0379)	(0.0652)	(0.0656)
Non-Agricultural Patents Control	No	Yes	No	Yes
Baseline Controls	Yes	Yes	Yes	Yes
Observations (Counties)	2,290	2,290	2,290	2,290
R^2	0.355	0.454	-	-

Robust standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p <$

Table 3.16: US Agricultural Patents by County and Types of Agricultural Societies Therein, 1873

	(1)	(2)	(3)	(4)
	Agricultural Patents *OLS (in logs) Cross Section 1873*	Agricultural Patents *OLS (in logs) Cross Section 1873*	Agricultural Patents *Negative Binomial Cross Section 1873*	Agricultural Patents *Negative Binomial Cross Section 1873*
State Societies	**Std=0.033**	**Std=0.020**	0.345**	0.373*
	0.249	0.152	(0.163)	(0.204)
	(0.206)	(0.170)		
Corresponding Societies	**Std=0.189**	**Std=0.082**	0.194***	0.196***
	0.216***	0.0935***	(0.0584)	(0.0593)
	(0.0285)	(0.0269)		
Non-Corresponding Societies	**Std=0.065**	**Std=0.017**	0.0824	0.0804
	0.0873***	0.0242	(0.0686)	(0.0683)
	(0.0306)	(0.0281)		
Non-Agricultural Patents as Control	No	Yes	No	Yes
Baseline Controls	Yes	Yes	Yes	Yes
Observations	2,268	2,268	2,290	2,290
R^2	0.357	0.450	-	-

Robust standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Chapter 4

Why did Britain build its Knowledge Access Institutions?
The 'Enlightenment Subsidy'

In the previous two chapters I showed that the blossoming of Knowledge Access Institutions (KAIs) in eighteenth and nineteenth century Britain facilitated the British Industrial Revolution. But why did KAIs blossom in the first place? Were they a response to industrialisation, stimulated by scale and demand for ongoing innovation in the revolutionising textiles, mining and iron making sectors? As such, is it misleading to think of KAIs as an exogenous cause of the British Industrial Revolution? Indeed, the alternative view, of endogenous learned societies, mechanics institutes and other institutions comprising the KAI infrastructure has a rich lineage in the historical literature, dating back to Marx and Engels (Engels 1895). This view has often been expressed in support of the claim that science owed more to the Industrial Revolution than the Industrial Revolution owed to science (e.g. O'Grada 2014).

In this chapter, I argue against the endogenous view of KAIs on two grounds. First, market-based incentives do a poor job of inducing innovative effort, even at the best of times (Nelson 1959, Arrow 1962, Tirole 1988). The conditions for endogenous innovation in the United States since World War II have been unprecedentedly supportive, yet US innovation during that period has relied heavily on government subsidy. The claim that innovation, and hence KAIs, were purely endogenous to the British Industrial Revolution asks far too much of eighteenth and early nineteenth century British market forces.

Second, since market forces in eighteenth and nineteenth century Britain were not plausibly strong enough to induce Britain's system of KAIs and since there was no major government subsidy to innovation as in the twentieth century US case, the growth of KAIs and the high level of innovation during the British Industrial Revolution presents a puzzle. Who funded Britain's KAIs and why, if not for profit? I argue that the answer to this puzzle lies in the multifaceted demand for science and KAIs in eighteenth and early nineteenth century Britain, much of it reflecting non-profit related motives. Eighteenth and early nineteenth century British culture was deeply influenced by the popular Enlightenment and within the resultant milieu, science served as an ideology, entertainment, social status symbol and a strategic political and religious asset. These cultural sources of demand for science made a career in science pay in eighteenth and early nineteenth century Britain. As such, the Enlightenment effectively subsidised the construction and running costs of the world's first R&D infrastructure. I provide empirical evidence for this argument by noting that Rational Dissenters – a group of co-religionists who based religious belief on scripture and reason alone, incorporating Newtonian science and the scientific method into theology and worship – exhibited a particularly high demand for science and KAIs. I show that there is a correlation across England between the geographic prevalence of Rational Dissent and early adoption of KAIs. I control for confounding variables, and the endogeneity of Rational Dissent to industrialisation using an instrumental variable approach based on the Five Mile Act of 1665, under which Charles II banished Rational Dissent from parts of Britain.

However, although KAIs were not fully endogenous to the British Industrial Revolution, neither were they fully exogenous. Rather, feedback effects via industrialisation were important to their blossoming, just as feedback effects more generally were important to the economic and social 'phase transition' at the heart of the British Industrial Revolution. Indeed, it is difficult to explain the British Industrial Revolution without appealing to feedback effects and those inherent to the growth of the R&D infrastructure might have played an important role.

The 'Endogenous View' of KAIs

The conventional wisdom has long held that the learned societies and mechanics institutes that comprised Britain's eighteenth and nineteenth century core KAIs were stimulated by industrial, rather than cultural, demand. Moreover, this claim has been advanced in the context of the broader argument that the correlation between the Industrial Revolution and scientific progress was due to the impact of industrialisation on science, rather than the other way around. Clearly, this argument is in the spirit of Marxist cultural determinism. Indeed, Engels expressed the case succinctly in 1895[48], when he wrote in a private letter that: "If society has a technical need, that helps science forward more than ten universities." In 1913 Elie Halevy wrote "it is in industrial

[48] Letter from Engels to H. Starkenburg, Jan 25th 1895 (Cunningham Wood 1988)

England with its new centres of population and civilization, that we must seek the institutions which gave birth to the utilitarian and scientific culture of the new era. At Manchester first, centre of the cotton industry, a species of local academy, a literary and scientific club was founded" (Halevy 1913).

Mid-twentieth century Marxist scholars adopted these assumptions too. In 1939, J. D. Bernal wrote "it was in Leeds, Manchester, Birmingham, Glasgow and Philadelphia, rather than Oxford, Cambridge and London, that the science of the Industrial Revolution took root." Science was necessary "for directors of industry," and some knowledge of scientific principles "was also becoming increasingly desirable for leading operatives." (Bernal 1939). S. F. Mason argued similarly that "the men of the industrial regions with their scientific education and their technical interest forwarded institutions to promote the arts and sciences in their own localities…The Manchester Literary and Philosophical Society arose from the meetings of scientists and industrialists." (Mason 1953). J. H. Plumb wrote "By 1815 every provincial town of importance had its society on the model of Manchester's, supported by both the local aristocracy and the local manufacturers. No other aspect of English cultural life had such whole-hearted middle-class support, because the intention was completely and avowedly utilitarian – the search for useful knowledge which would maintain England's industrial supremacy." (Plumb 1950)

These views are echoed by modern day scholars, who have married the endogenous view of KAIs with the claim that they were ineffective in generating technological innovation. In the Cambridge History of Science series from 2003, McClellan III writes "The principle answer" to the question of why eighteenth century Britain witnessed the rise of scientific societies "concerns the perceived usefulness of these institutions" while declaring in the same essay, "Plainly and tellingly, the early Industrial Revolution developed without significant input from eighteenth-century academies or universities (McClellan III 2003, p105)". Recently, in a rebuttal of Margaret Jacob's study of the role of scientific culture in the British Industrial Revolution, O'Grada writes "Yet while such societies lent scientific knowledge respectability, their role in spreading it was limited" (Jacob 2014, O'Grada 2014 p4).

KAIs and the Tragedy of the Knowledge Commons

Though the endogenous view of KAIs is widely held, economic theory tells us that it takes a lot for granted. This is because the market does a poor job of incentivising innovative effort, even at the best of times. Indeed, the rapid rate of technological innovation in the US since the Second World War, which was achieved under unprecedentedly supportive conditions for endogenous innovation, relied heavily on the financing of innovative effort by government. As I argue below, it seems reasonable to believe that around half of the 1.5% annual US total factor productivity growth experienced since WWII has ultimately been the result of non-endogenous innovative effort. During the British Industrial Revolution, however, the government provided no significant financing of innovative effort. Indeed, as such, it would be convenient to assume that the 0.7% annual TFP growth achieved at the peak of the British Industrial Revolution,[49] at half the post-WWII US rate, represents endogenous innovation, while the absence of government funding explains the 'missing half'.

However, these assumptions are implausible because the market conditions for endogenous innovation during the British Industrial Revolution were much weaker than those in the US during the twentieth century. An equal underlying rate of endogenous technological progress in the two cases would imply that endogenous innovation is highly inelastic to variation in market size and the appropriability of the returns to innovation. This seems too much to ask. The corollary is that the innovative effort that yielded 0.7% TFP growth per year during the peak of the British Industrial Revolution must have received significant exogenous support. And if innovative effort during the British Industrial Revolution was not fully endogenous to profit, then neither could have been the observed investment in the complementary factor of KAIs.

The tragedy of the knowledge commons

Technological progress is a cumulative process: new technology builds on the existing knowledge base established over generations. We are still reaping the social returns to the innovations of the Industrial Revolution. Nevertheless, it would be implausible to credit the incalculably large social return to the British Industrial Revolution over the past two centuries

[49] between 1830 and 1860 (Crafts 2014)

with having incentivised the innovative effort of Britain's inventors, even if these social returns were foreseen, *ex ante*, by an optimistic society. This is because market incentives offer only a weak mechanism for generating innovative effort.

It is difficult to appropriate the social return to invention. This is because of the economic characteristics of knowledge. Knowledge is a non-rival good – its consumption by one party does not preclude consumption by anyone else. Often, it is also non-excludable, or at best only partially excludable, meaning that one cannot typically appropriate much of the social benefit that it creates through productivity gains and consumer surplus (Romer 1990). Even if one has access to appropriation mechanisms such as patenting or secrecy, the rents that subsequently flow to contingent technologies are likely to accrue to somebody else. The upshot is that the appropriable private return to innovative activity is much smaller than the social return, even in the presence of well-functioning appropriation mechanisms, but particularly so when these mechanisms are absent or function poorly. As such, agents motivated by private profit undersupply innovation from the perspective of the social good (Nelson 1959, Arrow 1962, Tirole 1988).

This argument can be explored formally for the case of the British Industrial Revolution using the Romer-Mokyr model. Consider the following static version, where output is a function of labour in the manufacturing sector and the stock of propositional and prescriptive knowledge. The prescriptive knowledge stock is a function of the propositional knowledge stock and R&D labour, while the propositional knowledge stock is a function of past invented technology, which 'spills over' into the propositional knowledge base through its physical embodiment, dissemination through patent specifications, other literature or verbal communication (Bottomley 2015). These spillovers raise the future productivity of R&D labour, this impact being particularly large in the case of macroinventions or knowledge access devices. Hence:

$$Y = F(L_M, \lambda, \Omega)$$

$$\lambda = \lambda(L_R, \Omega)$$

$$\Omega = \Omega(\lambda)$$

All labour is either allocated to manufacturing or R&D:

$$L = L_M + L_R$$

and in the market equilibrium, the marginal private product of labour in both activities is equal, so that

$$w^{market} = \frac{\partial F}{\partial L_M} = \frac{\partial F}{\partial \lambda}\frac{\partial \lambda}{\partial L_R}$$

However, although the marginal social and private products are identical in the case of manufacturing labour, they are not in the case of R&D labour. The marginal social product of R&D labour includes, in addition to the direct marginal product of prescriptive knowledge, the marginal product of the propositional knowledge spillover,

$$\frac{\partial F}{\partial \lambda}\frac{\partial \lambda}{\partial L_R} + \frac{\partial F}{\partial \Omega}\frac{\partial \Omega}{\partial L_R}$$

Hence, in the market equilibrium, the marginal social product of manufacturing labour is lower than the marginal social product of R&D labour, which means that innovative effort is depressed relative to the socially optimal level. Labour could be re-allocated from manufacturing to research at a gain to aggregate output.

How much is the rate of endogenous economic growth depressed by the wedge between the private and social return to innovation? Empirical estimates for the modern economy suggest that the effect is quite large. Three meta-studies: Hall et al (2009), Griffiths, on behalf of the Institute for Fiscal Studies (2000) and Frontier Economics, on behalf of the UK Government's Department for Business, Innovation and Skills (2014), collate empirical estimates of the ratio of social to private returns to innovation, concluding that social returns appear to be around two to three times larger than private returns. These estimates are derived from regressions of total factor productivity on R&D expenditure and are likely to be an underestimate since they do not count long-lag social returns (Jones & Williams 1998). Bloom, Schankerman and Van Reenan (2013) measure social returns while also accounting for the negative externality of innovation due to the 'business stealing effect' captured in Schumpeterian models of innovation. They find that knowledge spillovers dominate business stealing, finding overall social returns at least twice the size of private returns.

Subsidy to innovative effort: Theory

This knowledge commons problem is solved when innovative effort is subsidised to raise the ratio of private return to social return. The scope for raising the incentive to innovate in this way can be investigated by finding the optimal subsidy rate μ to R&D wages in the Romer-Mokyr model. Define μ as follows: $w^{optimal} = w^{market}(1+ \mu)$, where $w^{optimal}$ is the optimal post-subsidy R&D wage and w^{market} is the prevailing pre-subsidy R&D wage. Note that in the socially optimal allocation, wages satisfy

$$w^{optimal} = \frac{\partial F}{\partial L_M} = \frac{\partial F}{\partial \lambda}\frac{\partial \lambda}{\partial L_R} + \frac{\partial F}{\partial \Omega}\frac{\partial \Omega}{\partial L_R}$$

Now, let β be the ratio of $\Omega(\lambda)$ to λ, then

$$\Omega(\lambda) = \beta\lambda(L_R, \lambda)$$

Hence,

$$w^{optimal} = \frac{\partial F}{\partial L_M} = \frac{\partial F}{\partial \lambda}\frac{\partial \lambda}{\partial L_R} + \frac{\partial F}{\partial \Omega}\frac{\partial \beta\lambda}{\partial L_R}$$

Using the product rule, specifically a special case of it known as the 'constant multiple rule', we can make the following substitution:

$$\frac{\partial \beta\lambda}{\partial L_R} = \beta\frac{\partial \lambda}{\partial L_R}$$

so that

$$w^{optimal} = \frac{\partial F}{\partial L_M} = \left(\frac{\partial F}{\partial \lambda} + \beta \frac{\partial F}{\partial \Omega}\right) \frac{\partial \lambda}{\partial L_R}$$

Substituting in μ and re-arranging gives the optimal subsidy:

$$\mu = \beta \left(\frac{\partial F}{\partial \Omega} \Big/ \frac{\partial F}{\partial \lambda}\right) = \beta . MRTS(\Omega, \lambda)$$

where $MRTS(\Omega , \lambda)$ is the marginal rate of technical substitution between Ω and λ, i.e. the ratio of the marginal product of the knowledge spillover to the private return. Clearly, if spillovers are large then there exists significant scope to raise the level of output by subsidising innovative activity. If these spillovers were large in eighteenth century Britain, then the emergence of a subsidy may have played a significant role in the acceleration of innovation during the British Industrial Revolution.

Subsidy to innovative effort: Post-WWII historical experience

R&D subsidies have been central to the supply of innovation at the world technological frontier during the strong period of technological innovation experienced in the decades since the Second World War. Between 1953 and 2011 in the US just less than half of all R&D expenditure was financed by non-profit sources. As tables 4.1a and 4.1b (based on National Science Foundation data) show, although 72% of R&D was carried out by private firms, only 56.8% was funded by private firms. The government funded 38.9%, universities 2% and non-profits 2.3%, each of which should be considered exogenous subsidies. Likewise, for the UK, Goodridge, Haskel, Hughes and Wallis (2015) show that in 2011 of the £22.5bn financed domestically, only just over half, £12.5bn (55%) was funded by private business enterprise while £8.3bn (37%) was funded by the government (including research councils) and £317m (1.4%) by higher education.

Table 4.1a: % of US R&D by funding source, 1953-2011 (calculated using constant 2009$)

	Basic	**Applied**	**Devel.**	Total
Business	19.4	54.4	66.9	**56.8**
Government	63.6	40.1	32.3	**38.9**
Universities	8.9	2.7	0.0	**2.0**
Non-profits	8.1	2.7	0.7	**2.3**

Source: NSF

Table 4.1b: % of US R&D by performing sector, 1953-2011 (calculated using constant 2009$)

	Basic	**Applied**	**Devel.**	Total
Business	19.7	65.4	86.9	**71.7**
Government	9.6	13.7	9.1	**10.2**
Universities	59.3	15.2	2.0	**13.9**
Non-profits	11.4	5.7	2.0	**4.3**

Source: NSF

Moreover, splitting US R&D between 1953 and 2011 into basic, applied and developmental reveals that exogenous subsidies likely had a disproportionately large impact.[50] Evidence suggests that social returns are larger in the case of basic than applied and developmental R&D (Akcigit, Hanley & Serrano-Verlade 2013). As table 4.1a shows, exogenous subsidies financed a highly disproportionate share of basic R&D compared to the other types. The government funded 63.6% of basic R&D, universities 8.9% and non-profits 8.1%, totalling 80.6%, compared to business' share of 19.4%.

One must consider the marginal impact of these subsidies. If subsidies merely crowd out private funding that would otherwise be forthcoming then the marginal effect of subsidies

[50] According to the NSF, basic R&D refers to a "systematic study to gain more comprehensive knowledge or understanding of the subject under study without specific applications in mind" while applied research is defined as a "systematic study to gain knowledge or understanding to meet a specific, recognized need" and developmental R&D refers to the development of specific pre-existing technology. http://www.nsf.gov/statistics/seind10/c4/c4s.htm#sb2

could be much smaller than their share of funding would suggest. Using data for the UK in the early twenty first century, however, Haskel et al. find that public sector R&D funding does not crowd out private sector R&D funding but rather 'crowds it in' by raising the productivity of private R&D (Haskel Hughes, Bascavusoglu 2014).

In her 2011 book *The Entrepreneurial State*, Mariana Mazzucato documents the role of the public sector in twentieth century innovation (Mazzucato 2011). She notes that 75% of new molecular entities approved by the US Food and Drug Administration between 1993 and 2004 were based on research by the government-funded National Institutes of Health labs. In IT, the US government's National Science Foundation funded the algorithm behind Google's search engine and early funding for Apple came from the US government's Small Business Investment Company. Moreover, "all the technologies which make the iPhone 'smart' are also state-funded ... the internet, wireless networks, the global positioning system, microelectronics, touchscreen displays and the latest voice-activated SIRI personal assistant." Apple's consumer products were based on seven decades of state-supported innovation.

One objection to this line of reasoning is that the share of the exogenous subsidy in the financing of R&D stated above would be overestimated if R&D statistics systematically overlooked a portion of innovative effort in the private sector. R&D statistics are designed to capture all deliberate expenditure on innovation – however, both theory and evidence suggest that many of the proximate gains to TFP are achieved through 'learning by doing', the indirect contribution to productivity growth that accrues during the process of using technology in production. The concept was first formalised in the context of a growth model by Arrow in 1962, having first been identified empirically for the aircraft industry in 1936 by Wright, who measured *learning curves*, tracing the output-input ratio for the production of particular models over time following their introduction.[51]

Is there more learning by doing in the private sector than the public sector? Should one count learning by doing as innovative effort? Private sector learning by doing is indeed likely to have been greater than public sector learning by doing because output and the capital stock are larger in the private sector. However, learning by doing is by definition an unfinanced

[51] For a recent empirical study of learning by doing in the automobile industry see Levitt, List & Syverson (2013)

externality of production. It should not be aggregated alongside R&D expenditure but rather thought of as a downstream process. The impact of learning by doing on TFP is contingent upon the technology produced by upstream R&D effort. Without marginal R&D effort, the returns to learning by doing would eventually run out. R&D is the ultimate source of TFP gains while learning by doing is the proximate source of the same gains. The complementarity between R&D and learning by doing is formalised in an endogenous growth model by Alwyn Young (Young 1993).

Given the R&D expenditure data and discussion above, what would be a reasonable decomposition of the contributions of endogenous and subsidised US TFP growth since the Second World War? It appears reasonable to attribute the bulk of TFP growth ultimately to R&D expenditure of one kind or another as endogenous growth models envisage. Empirical estimates of the social return to R&D suggest a value of around 50% to 85% (Hall et al. 2009, Frontier Economics 2014). Since the average share of R&D in US GDP since the Second World War is 2.5%, this implies that R&D investment could plausibly account for the 1.5% average annual US TFP growth during that period. A half and half split seems a reasonable decomposition of this 1.5% annualised gain between the impact of public and private R&D expenditure. As illustrated above, although the private sector share is slightly larger overall, the public sector disproportionately funds basic R&D, which exhibits higher social returns. As such, if one very crudely takes away the ‘exogenous component’ of US TFP growth since the Second World War, one is left with around 0.75% of annual endogenous TFP growth.

This rate is very close to the 0.7% annual rate of TFP growth achieved at the apex of the British Industrial Revolution, as based on Crafts’ estimates (Crafts 2014). Given the similarity, it would be convenient to assume that this 0.7% rate of TFP growth represents endogenous growth and that growth during the British Industrial Revolution was of a purely endogenous form, Meanwhile, the differential between nineteenth century British TFP growth of 0.7% and post-WW2 US TFP growth of 1.5% is essentially attributable to twentieth century US government subsidies. Certainly, there were no subsidies along the lines of tables 4.1a and 4.1b in eighteenth and nineteenth century Britain. However, this is assumption is implausible. As Crafts has explored (Crafts 1995), the conditions for endogenous growth during the British Industrial Revolution were much poorer than those in the US during the second half of the twentieth century. To attribute all the TFP growth during the British Industrial Revolution to endogenous innovation would be to assume that endogenous growth is highly inelastic to its underlying factors, which differed markedly between the British Industrial Revolution and the post-WWII US economy.

The Incentives for Innovation: the British Industrial Revolution versus the Post-WWII Technological Frontier

Endogenous growth theory emphasises the impact of market size and the presence of appropriation mechanisms on innovation, both of which were far less supportive during the British Industrial Revolution than in the US since WWII. Indeed, after surveying the conditions for innovation in eighteenth and nineteenth century Britain, Crafts concludes that endogenous growth theory is at least as useful in explaining why British growth was so slow during the British Industrial Revolution as why it was faster than previous experience (Crafts 1995, 1996). The the market was much smaller than in the modern US economy and access was poorer given less developed transportation technologies. This is true both when considering domestic markets only and when incorporating addressable foreign markets.

There is a wide gulf also in the availability and quality of appropriation mechanisms in the two cases. The literature on appropriation mechanisms distinguishes between legal and strategic mechanisms (Levin et al. 1987, Cohen et al 2000). The main legal mechanism is patenting.[52] Nuvolari and Macleod (2010) explain the problems of the British patent system during the Industrial Revolution,[53] and although the post-war US patent system has its problems too (see Bessen & Meurer 2009) it is clearly superior. Strategic appropriation mechanisms amount to secrecy, exploiting lead time and controlling complementary assets. These appear to have been easier to execute in modern day America than during the British Industrial Revolution due to the presence of the large corporation as a form of industrial organisation. Vertical integration has made controlling complementary assets easier, and scale economies have made lead time more exploitable.

Before exploring the appropriation mechanisms available during the British Industrial Revolution and the post-WWII US in greater detail, first, I present evidence on outcomes of appropriation in both cases. Knick Harley has studied profit rates in the textile industry during

[52] In addition to the minor legal mechanisms of utility models and industrial designs
[53] The major contributions are Dutton (1984), Macleod (1988) and Bottomley (2015)

the British Industrial Revolution, the main sectoral locus of technological innovation. He finds that the profit rates of major firms in the parts of the industry transformed by technological change were no higher than those in the parts of the industry that had not yet been transformed (Harley 1998, 2012). In cotton spinning, which had been revolutionised by major inventions, Samuel Greg and Partners earned average profits of 12% from 1796 to 1819 and William Grey and Partners made less than 2% per year between 1801 and 1810. At the same time, however, Richard Hornby and Partners, operating in the weaving sector, which was not mechanized until the 1810s, made an average profit of 11% between 1777 and 1809.

Greg Clark documents that the major textile inventors rarely made a fortune from their inventions despite the enormous social returns they produced (Clark 2007). John Kay (flying shuttle, 1733) was impoverished by litigation costs trying enforcing his patent, had his house destroyed by machine breakers in 1753 and died in poverty in France; James Hargreaves (spinning jenny 1769) had his patent application denied, was forced to flee by machine breakers in 1768 and died in a workhouse in 1777; and Richard Roberts (self-acting mule 1830) died in poverty in 1864, his patent revenues having barely covered his development costs. Even those of the great textile inventors who made money, did so late in their careers many years after their invention made its impact. Samuel Crompton (mule 1779), who made no attempt to patent, was granted £5,000 by parliament in 1811; Edmund Cartwright (power loom 1785), whose patent proved worthless and had his factory burned by machine breakers in 1790, was granted £10,000 by parliament in 1809; and Eli Whitney (US, cotton gin 1793) whose patent also proved worthless, made money later in his career as a government arms contractor. Even Richard Arkwright (water frame 1769), by far the most financially successful of the group, who was worth half a million pounds at his death in 1792, made most of his fortune after 1781 when other manufacturers had stopped honouring his patent, illustrating the unpredictability of the available appropriation mechanisms during the era. More generally, studying the wills of the rich in the nineteenth century tells us that despite the extraordinary growth of the British textile industry during the Industrial Revolution, only a handful of textile industrialists became very wealthy. Of the 379 people who died in the 1860s leaving estates of more than £0.5 million, only 17 (4%) were in textiles (Clark 2007).

Clark argues that the basic problem for innovators in the textile industry during the British Industrial Revolution, as in the other sectors of major technological advance (coal mining, iron and steel and the early railroads) was that productivity gains translated into price reductions rather than supernormal profits (Harley 1998, 2012, Clark 2007). The 90% reduction in man-hours required to produce a pound of cotton between the 1760s and 1860s – which produced over half of the British economy's overall efficiency gains during the Industrial Revolution, and by 1860 raised annual British economic output to a level 27% higher than it would otherwise have been – benefitted consumers, rather than enriching the innovators. Invention was not a reliable way to get rich during the British Industrial Revolution.

How does this picture compare with the current era? Aswath Damodaran, Professor of Finance at the Stern School of Business at New York University, provides regularly updated company financial data aggregated by industry.[54] His US database covers 95 industries based on 7,887 underlying US companies, including all 4,240 US companies publicly listed on major exchanges[55] and 3,647 on the Over the Counter Bulletin Board (OTCBB).

In 2014, the ten US industries with the highest net R&D expenditures to sales ratios had significantly higher profit margins than the economy overall. These industries were biotechnology, healthcare IT, software (system and application), software (internet), electronics (consumer and office), advertising, drugs (pharmaceutical), semiconductor, semiconductor equipment, and computers/peripherals, comprising 1,555 of the total 7,887 companies. Although they accounted for only 6% of 2014 sales and 8% of 2014 capital expenditures, they accounted for 86% of 2014 net R&D expenditures. The aggregated profit margin in these ten industries, as measured by the ratio of aggregated EBITDA[56] to sales, was 25%, compared to a 15% average across all industries, and their profit margin excluding current year R&D expenditures[57], was 37%, compared to a 17% average across all industries. The return on capital in these ten industries was also much higher than average, at 22% compared to 7%. This finding mirrors estimates of the relative returns to R&D and corporate capital in general in the US. Estimates of the private return to R&D in the US in the late twentieth and early twenty first centuries cluster at around 25% (Frontier Economics 2014), while James Poterba finds that the return to corporate capital between 1959 and 1996 averaged 8.5% (Poterba 1998).

[54] This database is located at http://pages.stern.nyu.edu/~adamodar/ , At the time of writing the database was last updated in January 2015.
[55] including US companies listed on major foreign exchanges such as the London Stock Exchange and AIM
[56] earnings before interest, taxes, depreciation and amortization
[57] measured using the ratio of aggregated EBITDAR&D (earnings before interest, taxes, depreciation and amortization and R&D expenses)

Why were the private returns to innovation greater in the post-WWII US economy than during the British Industrial Revolution? One reason is that patenting was much more expensive during the British Industrial Revolution. Securing a patent for England and Wales prior to the patenting reforms of 1852 cost around £100 and extending it to Scotland and Ireland cost a further £200 to £250. Patenting also required a great amount of effort and time, as the process of securing the patent in England and Wales involved obtaining the signatures of seven different offices, including the signature of the sovereign at two separate stages. The diary of one inventor in the 1720s shows that he spent five months in London petitioning for his patent – although by 1829 it appears that the average length of time taken was only about two months (Bottomley 2015). Scottish and Irish coverage required further signatures, the average length of time taken to obtain these during the first half of the nineteenth century appearing to be around six weeks for Scotland and two months for Ireland. Given the complexities of the process, patent agents were increasingly used as the Industrial Revolution progressed. This added a further £40 to £100 of cost (Dutton 1984). These costs compare to the average weekly wage of a skilled worker of between £1 and £2, meaning that the ratio of patenting costs to a skilled worker's weekly wage was around 67 to cover England and 216 to cover the United Kingdom (not counting the opportunity costs of time spent navigating the process). As such, access to the patent system was heavily restricted to the wealthy. In the case of the modern US patent system, the website 'IP Watch Dog' estimates the cost of securing a 'high quality' patent with the intent of obtaining strong patent protection at around $10,000 to $20,000, including attorney fees[58]. This compares to the weekly wage of a bachelor's degree holder of around $1,100 in 2014 (and around $1,600 for a doctoral or professional degree holder), giving a ratio of patent cost to the weekly wage of a 'skilled worker' of around 14. The modern US patent system is much more accessible than the British system during the Industrial Revolution.

The reliability of the patent system during the British Industrial Revolution remains a controversial question. Dutton (1984) and Macleod (1988) illustrate the weakness of patent litigation, emphasising a reluctance of judges to uphold patents. Based on a sample of 82 cases between 1770 and 1829, Dutton found that only about one-third of decisions under common law fell in favour of patentees. Sean Bottomley has recently presented a revised analysis that puts the system in a significantly better light, finding that, based on an expanded sample of patent cases, around half of patent litigations were successful (Bottomley 2015). Even so, this

[58] http://www.ipwatchdog.com/2015/04/04/the-cost-of-obtaining-a-patent-in-the-us/id=56485/

success rate is lower than in the modern-day US, where between 1995 and 2013, 66% of the patent cases that were decided at trial were won by the patentee (Price Waterhouse Coopers 2014).

The predictability of patent litigation during the British Industrial Revolution was also hampered by minimalistic legal foundations and the limited history of cases upon which to base common law. Up until 1852 the basis for patent law was the Statute of Monopolies, which was instituted in 1623 following a conflict between James I and parliament concerning the king's abuse of his prerogative powers in granting licences of monopolies to favoured parties. The statute restrained such licences but exempted patents for new inventions, applicable to "the first and true inventor" of "new manufactures under this realm". Cases concerning patents were to be determined under common law, the only statutory guidance being that patents were limited to fourteen years and must not contradict the public interest. Patents were not required to be examined, although a written specification was required from 1778. As such, courts were required to improvise decisions under common law with no sound underpinning in statue law nor a broad base of precedents and, without examination, patents were awarded tenuously. In 1795, Chief Justice Eyre, presiding over *Boulton and Watt vs Bull*, lamented that "patent rights are nowhere that I can find accurately described in our books" (Nuvolari & Macloed 2010). At parliament's 1829 investigation into the patent system – the first since the 1623 statute – a witness told the select committee that "there being no existing basis of law, the dictum of the judge is one thing one day and another thing another' and Marc Isambard Brunel declared "I might as well toss for the fate of a patent" (Select Committee on Patents 1829: 454, 486).

The US patent system during the late twentieth and early twenty-first centuries has been somewhat beleaguered by the quality of patent examination and the predictability of litigation (Bessen and Meurer 2009). For instance, using a sample of 980 litigated patents between 2000 and 2010, Miller (2013) estimates that 28% of all patents granted would be found at least partially invalid if subject to an 'anticipation' or 'obviousness' decision in litigation. Nevertheless, it would be an extreme claim to suggest that US patent examination adds no value at all to upholding of the quality of US patents and predictability of litigation.

A major problem in the modern US patent system is the usage of 'tactical patenting', where companies file patents to trap another entity in patent infringement. Cohen et al (2000) found by surveying 765 firms engaged in patenting that although the most common reason for patenting was to prevent imitation (95.8% of respondents with respect to product innovations and 77.6% for process innovations), blocking was also common (81.2% for product, 63.6% for process), and to a lesser degree, so was taking out a patent 'for use in negotiations' (47.4% for product, 37.0% for process). In recent years, tactical patenting has become an acute problem due to the rise of 'patent assertion entities' (PAEs), which do not engage in R&D but purchase large quantities of patents from patentees to earn a spread between litigation revenues and the purchase price of the patent. In 2013, PAEs filed 67% of all new patent infringement cases, up from 23% in 2009. This may have inhibited innovation by increasing the risk of inadvertent infringement. Research shows that firms that engage more in R&D are more likely to be sued for patent infringement by PAEs (Bessen and Meurer 2013), and that being successfully sued by a PAE reduces subsequent R&D expenditure and patenting (Tucker 2014, Smeets 2014, Cohen et al 2015).

PAEs pose a considerable problem for the US patent system today, but this problem was much smaller prior to the past decade or so. Moreover, although tactical patenting has indeed presented challenges during the entire post-WWII period, it also presented challenges during the British Industrial Revolution. For example, James Watt's extended patent for the separate condenser is the canonical example, which while in force from 1769 until 1800 appears to have long delayed the development of the subsequent generation of steam engines (Bottomley 2015). Overall, given far lower costs and the presence of patent examinations, the post-WW2 US patent system has been superior to the system in place during the British Industrial Revolution. This is likely to have contributed to the superior conditions for endogenous growth.

Strategic appropriation mechanisms (secrecy, the exploitation of lead time and the strategic ownership of complementary assets) were important in both periods. Cohen et al's 2000 survey revealed that of 1,118 companies engaged in product innovation, 35% patented, while 53% exploited lead time, 51% used secrecy and 46% exploited control of complementary manufacturing. Of 1,087 companies engaged in process innovation, only 23% patented, while 50% used secrecy, 37% lead time and 43% complementary manufacturing. Likewise, during the British Industrial Revolution much innovation occurred outside of the patent system. Petra Moser has shown that only 11% of the British exhibits at the 1851 Great Exhibition were patented (Moser 2012). By matching patent data to the key inventors of the British Industrial Revolution as identified by economic historians of technology, one finds much higher patenting rates than this, but a significant role for non-patented innovation remains. For example, of Allen's 79 'great inventors', 68% patented (Allen 2009), and of Meisenzahl and Mokyr's 759 'tweakers', 60% patented (Meisenzahl & Mokyr 2011).

Strategic appropriation mechanisms worked more effectively in the post-WWII US economy than during the British Industrial Revolution because the 'modern industrial enterprise' made them easier to implement. First, vertical integration associated with the modern industrial enterprise facilitates the appropriation of technology rents through the ownership of complementary assets (Teece 1986). Second, large firms can scale up production of product innovations, thereby establishing a cost advantage relative to potential entrants (Chandler 1990). Without this structure, inventors found it difficult to appropriate the returns of innovation during the British Industrial Revolution. As Harley shows, the textile industry experienced rapid firm entry following innovation and the prices of output fell precipitously (Harley 2012). Policy was also unhelpful. Bottomley (2015) describes the proviso, in place until 1832, that if a financial interest in a patent was ever vested in more than five people then the patent would be immediately invalidated, frustrating capital-raising for expansion in production capacity or the purchase of complementary assets.

The Complementarity of KAIs and Innovative Effort

KAIs were an investment in the capital stock that was complementary to innovative effort. As such, if purely endogenous innovation during the British Industrial Revolution is implausible then so too are purely endogenous KAIs. Moreover, while KAIs raised the productivity and supply of innovative effort, at the same time, a greater supply of innovative effort raised the marginal productivity of the KAI capital stock. This mutually supportive relationship between KAI investment and innovative effort means that there must be two self-sustaining equilibria with respect to their joint prevalence in the economy.

Since the British economy lacked any meaningful pre-existing innovation infrastructure before the blossoming of KAIs and since technological innovation was slow and sporadic, it seems reasonable to assume that Britain was situated in a lower level equilibrium on the eve of the British Industrial Revolution: no KAIs and little innovative effort. Innovative effort was too low to warrant capital investment to support it and the existing innovative infrastructure was too small to make much difference to the productivity of innovative effort. It seems likely that Britain's transition to the equilibrium characterised by the accumulation of KAI capital and accelerating innovation required an exogenous impetus. Below, I make this case formally in the setting of a model inspired by Redding (1996).[59]

There are n entrepreneurs, each of whom lives for two periods and produces output according to the production function $L_{Mi}\lambda$, where L_{Mi} is the proportion of i's labour allocated to manufacturing. There is no saving or borrowing so each entrepreneur's consumption in period t is equal to their output in that period. In period one, entrepreneurs decide proportions of their labour to allocate to manufacturing and innovation. The innovation proportion μ_i results in the sacrifice $\mu_i\lambda$ of consumption in period one. However, this sacrifice pays off in period two when manufacturing output and consumption rise by $\mu_i\sigma\lambda$, where $\sigma>1$ is a parameter that represents the productivity of innovative effort. Hence, each entrepreneur faces the following maximization problem

$$\max_{u_i} \left\{(1-\mu_i)\lambda \; + \; \rho[\mu_i\sigma + (1-\mu_i)]\lambda\right\} \quad (4.1)$$

Next, consider an additional ($n+1^{th}$) entrepreneur, who can choose to spend a fraction v of his labour in period one operating a KAI. For simplicity, assume that if he chooses $v>0$ then he spends the remaining fraction of his labour, $1-v$, in manufacturing, and does not allocate any labour to innovation. If he chooses $v=0$ then his maximization problem is the same as that of the first n entrepreneurs.[60] The KAI increases the productivity of innovative effort for entrepreneurs 1 to n by the factor $1+\gamma v^{\theta}$, where $\gamma>1$ and $0<\theta<1$ are exogenous parameters. To compensate himself, entrepreneur $n+1$ extracts a fraction β of this producer surplus. Hence, entrepreneurs 1 to n face the modified maximization problem

$$\underset{u_i}{max} U_{i=1,\dots,n} \quad \left\{(1-\mu_i)\lambda \; + \; \rho\left[(1-\beta)\mu_i\sigma\left(1+\gamma v^{\theta}\right) + (1-\mu_i)\right]\lambda\right\} \quad (4.2)$$

---

[59] Redding modelled the complementarity of investing in education and investing in R&D in the context of endogenous growth.

[60] Relaxing this assumption and allowing him to allocate his labour to a combination of all three activities in period 1, i.e. to founding a KAI *(v)*, innovating (μ_i) and manufacturing ($1-v-\mu_i$), would be more realistic but also complicates the analysis considerably without substantively changing its conclusion.

And, restricting the behaviour of *1* to *n* to the symmetric case where $\mu_i = \mu$ for all i = 1,…,n, entrepreneur *n+1* faces the maximization problem:

$$\max_{(v,u_i)} U_{i=n+1} \begin{cases} (1-v)\lambda \ + \ \rho\big[\beta n\mu\sigma\big(1+\gamma v^{\theta}\big)+1\big]\lambda\,, & if\ v>0 \\ (1-\mu_i)\lambda \ + \ \rho[\mu_i\sigma + (1-\mu_i)]\lambda, & if\ v=0 \end{cases}$$

Now, conditional on $v > 0$, the first order condition for *n+1*'s optimal choice of *v*, *v**, is

$$\frac{\partial U_{i=n+1}}{\partial v} = \rho\beta n\mu\sigma\theta\gamma {v^{*}}^{\theta-1}\lambda - \lambda = 0,$$

and so

$$v^{*} = \min\{\,1, [\rho\beta n\mu\sigma\theta\gamma]^{\frac{1}{1-\theta}}\ \}$$

which is increasing in the probability that entrepreneurs *1* to *n* allocate effort μ to innovation. Alternatively, conditional on $v=0$, his optimal allocation to innovation μ_i is derived from the first order condition that arises from maximizing 4.1 with respect to μ_i:

$$\mu^{*}_{i=n+1} = \begin{cases} 1\,, & if\ \ \sigma > \dfrac{\rho+1}{\rho} \\ 0, & \text{otherwise} \end{cases}$$

which is also entrepreneur *1* to *n*'s optimal allocation of labour to innovation in this case. This means that without a KAI, if the productivity of innovation is large enough relative to the rate of time preference then innovation occurs, but if the productivity of innovation is too small relative to the rate of time preference then innovation does not occur.

Entrepreneurs *1* to *n*, in turn, choose innovative effort (i.e. μ) to maximize 4.2. Hence,

$$\mu^*_{i=1,\dots,n} = \begin{cases} 1, & \text{if } \rho(1-\beta)\sigma\left(1+\gamma v^{\theta}\right) > 2 \\ 0, & \text{otherwise} \end{cases}$$

The strategic complementarity between *n+1*'s KAI investment decision and the other *n*'s innovative effort decisions gives rise to the possibility of multiple equilibria, namely one with no investment in KAIs and no innovative effort: the *low innovation trap*, and one with both KAIs and innovative effort: the *innovation equilibrium*. For the innovation equilibrium to hold the following two conditions must be satisfied:

Condition 1:

$$\rho(1-\beta)\sigma\left(1+\ \gamma[\rho\beta n\sigma\theta\gamma]^{\frac{\theta}{1-\theta}}\right) > 2$$

so that the first *n* entrepreneurs choose to innovate when *n+1* invests in the KAI. Notice that this condition depends positively on the productivity of innovation.

Condition 2:

$$\Pi_{n+1}(v>0, \mu^*=1) > \Pi_{n+1}(v=0, \mu^*=1)$$

Entrepreneur *n+1* must choose non-zero *v* and as such he requires a large enough return on his KAI investment to beat his alternative return on innovating without the KAI. However, this return cannot be derived from too large an appropriation share β, which would discourage the other *n* entrepreneurs from using the KAI. So, we require that:

$$(1+\rho)+\rho\beta n\sigma(1+\gamma[\rho\beta n\sigma\theta\gamma]^{\frac{\theta}{1-\theta}})-[\rho\beta n\sigma\theta\gamma]^{\frac{1}{1-\theta}}>\rho\sigma$$

i.e. we need a large enough combination of β, n, and γ, but β can't be too large in relative terms, since that would violate condition one.

If either of conditions 1 or 2 does not hold then $v=0$. There is no KAI investment and the economy languishes in the low innovation trap. The important point is that this is a stable equilibrium. Moving to the high innovation equilibrium requires an exogenous shock to one of the parameters. In the remainder of this chapter, I investigate the shock of a subsidy τ, due to Enlightenment culture, to the return on KAI investment, $\rho\left[\beta n\mu\sigma\left(1+\gamma v^{\theta}\right)\right]\lambda$.

KAIs and the 'Enlightenment Subsidy' to Innovation

Although innovative effort was not subsidised by the government during the British Industrial Revolution as it has been since the Second World War, it was subsidised by the ideological and cultural preferences of a society 'electrified' by the European Enlightenment.

Circumstantial evidence of the exogeneity of KAIs

Three basic facts suggest that the roots of KAIs lay outside of the British Industrial Revolution itself. First, early KAIs were established long before the Industrial Revolution and although Britain's KAIs proliferated markedly during the Industrial Revolution, these early forerunners served as an important precedent, both ideologically and operationally. The Royal Society was founded in 1660 (chartered in 1662) a century before the British Industrial Revolution began. As discussed below, it was founded upon the Baconian ideology of the 1620s, which emphasised the public utility of knowledge, not private return. Britain's eighteenth and nineteenth century KAIs followed knowingly in its footsteps.

Second, the eighteenth and early nineteenth century blossoming of KAIs occurred alongside the broader growth of voluntary associational societies and clubs across Britain. Peter Clark estimates the number of newly established societies per decade as 100 in 1700, 200 in 1750, 400 in the 1760s, around 700 in the 1780s and over 1,000 in the 1790s, strongly outstripping population growth (Clark 2000). Moreover, this was a Western European-wide phenomenon and should be thought of as an aspect of the European Enlightenment. Clark writes (pp ix): "If the Enlightenment did exist, then one of its principle engines was the Georgian voluntary society. Fanning out across the English speaking world, clubs and societies may have served as vectors of ideas, new values, new kinds of social alignment, and forms of national, regional, and local identity". The Enlightenment was the process of diffusion of a set of ideologies. It was embodied by the formal and informal social networks along which those ideas and beliefs passed, which were often structured by Clark's broad range of voluntary societies. One strand of the Enlightenment was the 'Industrial Enlightenment', identified by Mokyr (2002), in which the ideas and beliefs that were disseminated concerned the value of knowledge for economic progress. At the hubs of its network were KAIs.

Third, while British industrialisation was concentrated in certain parts of the country, KAIs were spread far and wide. Figures 4.1 to 4.4 show the correlations across British registration districts in 1851 between the number of KAIs and KAI members (controlling for population) and proxies for industrialisation (the share of the workforce occupied in the secondary sector) and urbanisation (population density). These correlations are positive but low. There remains a great deal of variation in KAI prevalence to be explained by non-endogenous factors. Moykr points out that Jane Austen lived through the British Industrial Revolution though never mentioned industrialisation in her novels. She lived in the non-industrialising home counties, far from the north, midlands and black country and quite disconnected even from London (Mokyr 1999). Yet, her home town of Alton, Hampshire had three KAIs, in the form of the Alton Book Society (1805), the New Alton Book Society (1822) and the Alton Mechanics Institute (1837), the latter with 106 members and nearly one thousand books in its library in 1851.

Figure 4.1: KAIs versus Secondary Sector Employment Ratio by British Registration District (After taking Logs, and controlling for Log Population) Cor = 0.13

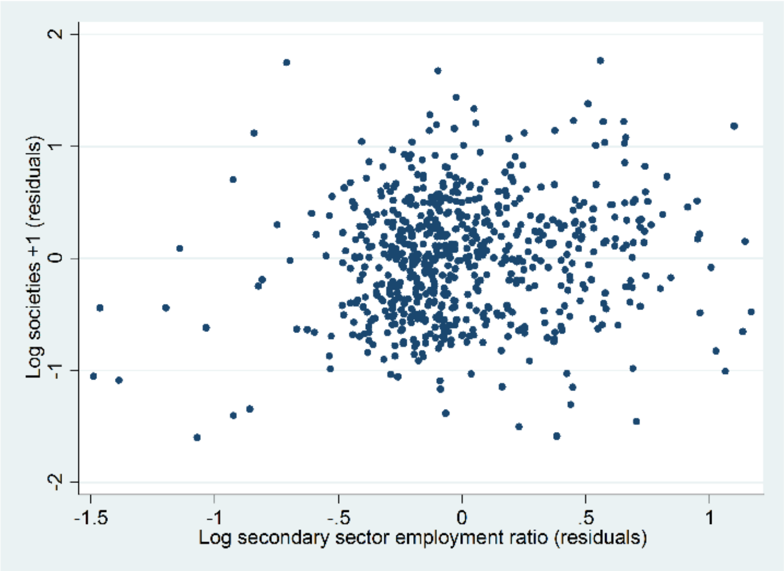


Figure 4.2: KAI members per Working Population versus Secondary Sector Employment Ratio by British Registration District (Logs) Cor=0.0095

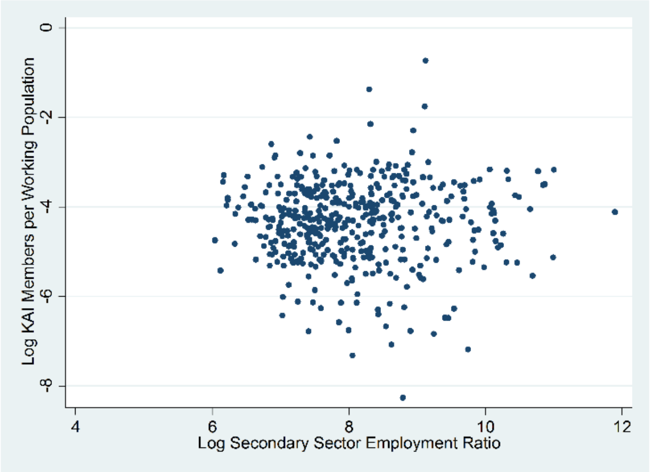


Figure 4.3: KAIs versus Population Density by British Registration District (After taking Logs) Correlation = 0.33

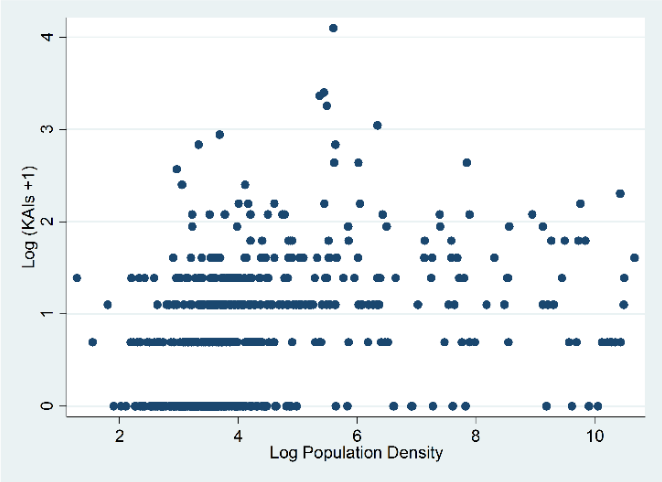
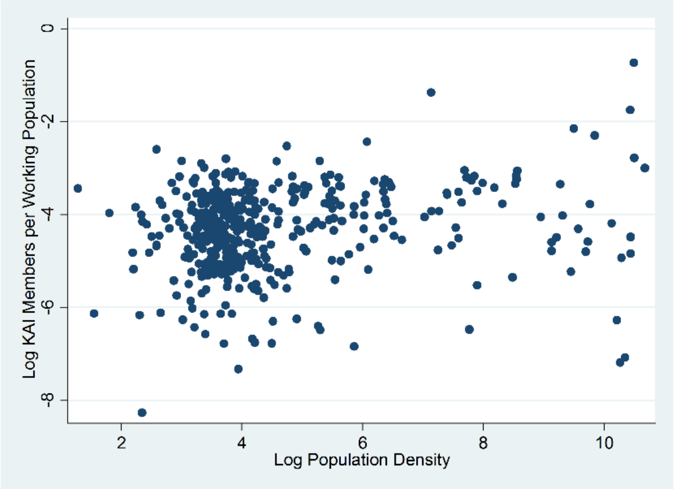


Figure 4.4: KAI Members per Working Age Population versus Population Density by British Registration District (Logs) Correlation = 0.18



The Enlightenment Subsidies of KAIs

The European Enlightenment profoundly influenced politics, society, economics, culture and religion (Porter 2000). Moreover, political revolutions, new civic structures, industrialisation and new cultural and religious beliefs each interacted with one another in complex ways. For example, adjustments to political institutions changed the conditions for economic growth and created more freedom for civic structures to develop. At the same time, the rising economic status of certain groups in society enabled them to shape political institutions. The Scientific Revolution was an important ingredient in many of the strands of the European Enlightenment (Jacob 2009, Wootton 2015). Locke, Hobbes and Rousseau brought the scientific method to bear on politics and Hume on ethics. Newtonians such as Samuel Clarke and Rational Dissenters such as Joseph Priestley applied it to religion**,** Adam Smith to economics and, ultimately, thousands of inventors and entrepreneurs to industry.

As such, as an individual living through the European Enlightenment one potentially would have had lots of reasons to engage with and invest in institutions that promoted science. Of course, this would depend upon one's place in society – political, social and economic change had many enemies, particularly among those with privileges and rents to lose, and the individuals who founded and engaged with KAIs tended to exhibit certain characteristics, as I explore below. In this way, as R&D institutions, KAIs were cross-subsidised by five non-profit utilities of science: 1) progressive ideology advocating the public good 2) religious insight 3) political asset, 4) social status symbol and 5) entertainment. Below, I explore the demand for these five utilities and provide falsifiable evidence of the link between Rational Dissenters and KAIs, which was emblematic of the Enlightenment subsidy.

Baconian Ideology: The Royal Society, founded in 1660, formalised the 'invisible colleges' of London and Oxford of the late 1640s and 1650s, informal gatherings of natural philosophers inspired by the ideology of Francis Bacon. In the 1620s, Lord Bacon advocated a programme of inquiry into the laws of nature using the scientific method to achieve the "relief of man's estate". In *The New Atlantis*, published in 1627, Bacon envisaged a "House of Salomon", a research academy constituting researchers who collected data and carried out experiments and tried to infer from the results general regularities and laws. This was the essence of the Royal Society, founded thirty-three years later.

Britain's provincial literary and philosophical societies founded in the eighteenth and early nineteenth centuries were based upon these Baconian principles and followed the operational format of the Royal Society, of a rotating elected governing committee, elected membership, subscriptions, regular meetings in which papers were read on diverse topics, the maintenance of a library and correspondence with other KAIs. They corresponded and shared members with the Royal Society.

The Society for the Encouragement of Arts, Manufactures and Commerce (today, the Royal Society of Arts) was founded in 1754 (granted a Royal Charter in 1847), and operated by awarding premiums (cash prizes) and medals for technological innovations. The premiums were not funded by government, nor generally by profit-making interests. Indeed, the society declined to award them to patented innovations. Rather, they were funded by membership subscriptions, which were paid by wealthy men acting upon Baconian notions of knowledge and the public good. The society's statement of intent, "the encouragement of the Arts, Manufactures and Commerce by the advancement of education in and the encouragement and conduct of research into the sustainable context within which the said Arts, Manufactures and Commerce may prosper and to make such research findings available to the public', was overtly Baconian. So too was that of the third major metropolitan KAI, the Royal Institution, founded in 1799 "for diffusing the knowledge and facilitating the general and speedy introduction of new and useful mechanical invention and improvements, and also for teaching, by regular courses of philosophical lectures and experiments, the application of these discoveries in science to the improvement of arts and manufactures, and in facilitating the means of procuring the comforts and conveniences of life".

The mechanics institutes founded in the early nineteenth century, expanded the Baconian programme to educating the lower classes. They were founded and run by members of local elite KAIs along the Baconian principle of the dissemination of knowledge for the public good. Their pioneer, George Birkbeck, a Yorkshireman appointed Professor of Natural Philosophy at Anderson's Institution in Glasgow in 1799 following his medical training at Edinburgh, wanted to provide mechanical operatives with knowledge of scientific principles, which he believed would make their work more efficient and pleasurable (Kelly 1992). In his first few weeks as a Professor he met some mechanical operatives in a tinman's shop who were constructing apparatus for his lectures, and decided to offer a course of lectures free of charge 'abound with experiments, and conducted with the greatest simplicity of expression and familiarity of illustration, solely for persons engaged in the practical exercise of the mechanical arts'. Later he remarked of the incident:

> I beheld, through every disadvantage of circumstance and appearance, such strong indications of the existence of the unquenchable spirit, and such emanations from 'the heaven lighted lamp in man', that the question was forced upon me, Why are these minds left without the means of obtaining that knowledge which they so ardently desire, and why are the avenues of science barred against them because they are so poor? It was impossible not the determine that the obstacle should be removed that much pleasure would be communicated to the mechanic in the exercise of his art, and that the mental vacancy which follows a cessation from bodily toil, would often be agreeably occupied, by a few systematic ideas, upon which, at his leisure he may meditate.

By the fourth lecture Birkbeck's audience had swelled to 500. In 1823, Birkbeck, now a physician in London, co-founded the London Mechanics Institute, which paved the way for a national movement of institutes numbering around 800 by mid-century. Baconian ideology is central to the history of KAIs.

Scientific Religion: The Scientific Revolution, ushered in by the introduction of the heliocentric Copernican model of the universe in 1543, dealt a blow to the authority of the church, both its Catholic and Protestant variants. Galileo, Descartes and Newton shattered the Scholastic interpretation of the Aristotelian description of the universe endorsed by the Catholic Church, which asserted that the earth was motionless at the centre of the universe and that objects possessed inherent natures that determined their actions (e.g. objects fell towards the earth because it was in their nature to do so). The Scientific Revolution replaced this doctrine with a mechanical system consisting homogenously of atoms, acted upon by the forces of attraction and repulsion, in which the Earth assumed an arbitrary location. Moreover, due to the homogeneity of matter and the consistency of the laws governing its motion, the entire system could be understood by experimentation (i.e. the heavens were subject to the same laws of motion as pocket pendulums) and described by mathematical formulae. This model of the heavens and the Earth raised severe problems for interpreting the bible. But the bigger problem for the church was the elevation of evidence and reason as sources of authority.

In the wake of the Scientific Revolution, religious attitudes splintered as theological interpretations of new scientific facts were explored. The tradition most commonly associated with the Enlightenment was atheism, which took hold in France (Gay 1966). However, in England the most influential tradition was probably the Anglican Latitudinarian interpretation of Newton's work, which saw God at the centre of Newton's mechanical system, visible in the forces of attraction and repulsion acting on bodies. Indeed, Newton's motive for writing the *Philosophiæ Naturalis Principia Mathematica* (1687) and *Opticks* (1704) was to support public belief in the deity in this way (Jacob and Stewart 2004). While relatively tolerant, the Anglican Latitudinarian position also emphasised the importance of a national church and an ordered society. It represented the English 'moderate Enlightenment', acting as a bulwark against the Enlightenment's radical tendencies and was expressed seminally by Samuel Clark, one of the leading public intellectuals of the era, in his Boyle Lectures of 1704 and 1705, which were published in eight editions in the subsequent decades. Furthermore, Shapiro (1968) has identified a correlation between Latitudinarians and science in the 1650s and in the founding of the Royal Society, indicating a relationship between moderate religious attitudes and English science.

The religious position that displayed the strongest direct link to KAIs, however, was Rational Dissent. It is distinguishable by two characteristics. The first was its adherents' dissent from the Church of England following the Act of Uniformity of 1662, which demanded the use of the Book of Common Prayer in religious service. This Act was established by Charles II along with three other associated legal statutes between 1661 and 1665[61] (including the Five Mile Act of 1665, which is central to the next section of the chapter) collectively named the Clarendon Code after Charles II's Lord Chancellor. The purpose of the Clarendon Code was to preserve the Church of England's hegemony in Restoration England following the religious sectarianism of the Civil War and the growth of radical new religions during the Interregnum. Just over two thousand clergymen and teachers refused to conform to the Act of Uniformity and, as such, were displaced from their posts, creating a permanent division in the English religious landscape.

Not all nonconformists were (or were to become) Rational Dissenters, however. Rather, the second characteristic that marked Rational Dissent was its adherent's adoption of 'natural religion' – an understanding of God based only on scriptural revelation and reason. The two characteristics were related because the Act of Uniformity required ministers to preach the doctrine of the Holy Trinity, to which Rational Dissenters objected because it was supported by neither scripture nor reason. Furthermore, the largest denominational group among Rational

[61] the Corporation Act (1661, which), the Conventicle Act (1664) and the Five Mile Act (1665).

Dissenters was that of the English Presbyterians, who had campaigned to reform the governance of the Church of England since 1570. The doctrine of the Trinity – established by the Council of Nicaea in AD 325, the first concerted attempt by the Christian church to reach doctrinal consensus across Christendom – represented exactly the kind of institutional distortion of religion that they had campaigned against.

Over time, Rational Dissent came to be defined by its position on the Trinity. Rational Dissenters' commitment to anti-trinitarianism was tested and their resolve strengthened during the eighteenth century by ongoing legal discrimination under the Clarendon Code, even as other variants of dissent regained their freedoms. The Act of Toleration of 1689, which overruled much of the Clarendon Code, excluded the toleration of nontrinitarians (alongside Catholics and atheists), nontrinitarian beliefs remaining illegal up until the passing of the Trinity Act in 1813. In 1774, however, the first Unitarian chapel was founded in Essex Street in London, giving birth to the formal denomination of Unitarianism – and despite its illegal status prior to the Trinity Act, most of the English Presbytarians converted to Unitarianism during the late eighteenth and early nineteenth centuries, joined in smaller numbers by former General Baptists and even some Anglicans (Watts 1978, 1993).

In his chapter on Unitarians and Quakers in D.G. Paz's 1995 edited volume *Nineteenth-century English religious traditions*, Robert K. Webb surveys the historiography of Unitarianism. While cautious of denominational self-written history, Webb notes the "Unitarian commitment to the objective and external authority of science and criticism" stemming from the commitment to natural religion (Webb 1995). Likewise, John Hedley Brooke (2006) explains the complementarity of the two defining characteristics of Unitarianism: "Fundamental to Unitarian belief was the right to liberty of conscience in religious matters. This belief sat comfortably with respect for the sciences, which could be hailed as paradigms of free enquiry."

These verdicts match Unitarian self-perception in the eighteenth century. Joseph Priestley, one of the fathers of denominational Unitarianism, defined Unitarianism as "the belief of primitive Christianity before later corruptions set in" (Morse Wilbur 1952), while he also emphasised the doctrinal significance of science in the rooting out of such corruptions: "this rapid progress of knowledge … will, I doubt not, be the means under God of extirpating all error and prejudice, and of putting an end to all undue and usurped authority in the business of religion as well as of science" (Hedley Brooke 2006). Even enemies of Unitarianism agreed on the nature of its characteristics, if not their virtue. In an attack published in 1826, Baden Powell noted their assumption that the human mind "enlightened by science in physical things, must be guided by analogy and congruity, and depend upon its own resources in the search after religious truth" (Hedley Brooke 2006).

Newton's anti-trinitarianism is well established (Jacob and Stewart 2004). Moreover, the nexus between science and Rational Dissent/Unitarianism in evident in the curricula of dissenting academies, higher education institutions established by Unitarians and Quakers to educate the sons of dissenters, non-Anglicans being unable to attend Oxford and Cambridge[62] (Rivers, forthcoming). These academies provided a superior training in science compared to Oxbridge until well into the nineteenth century, as can be seen, for instance, in Irene Parker's comparison of the scientific content of curricula at dissenting academies with that of Oxford University in the eighteenth century (Parker 1914). The relationship can also be seen circumstantially in the link between KAIs and Unitarians. Thackery documented the strong link between Unitarians and the Manchester Literary and Philosophical Society (Thackery 1974), while Inkster has found a disproportionate influence of the Unitarians in the scientific community in Sheffield (Inkster 1977) and Orange with respect to the Newcastle Literary and Philosophical Society (Orange 1983).

Margaret Jacob has argued that Unitarianism was the perfect religion for the science-loving entrepreneur at the heart of the British Industrial Revolution (Jacob 2000). Jacob shows that Max Weber's protestant capitalist, motivated to strive by Calvinist doctrine, is a poor description of the prominent entrepreneurial cliques of the British Industrial Revolution. Moreover, it is difficult to explain why Calvinist doctrine, particularly the doctrine of predestination, led to striving rather than to despair (Dowey 1952). Rather, by showing the central role that Unitarianism played in the lives of the Watt and Wedgewood families, she replaces Weber's Calvinist capitalist with a Unitarian capitalist. As she puts it, "Sixteenth-century Calvinism may have put striving into the psychological makeup of early Protestants, but…other patterns of thought had to be present before despair could be quietly laid to rest.

[62] Cambridge allowed non-Anglicans to matriculate but not graduate without swearing allegiance to the Church of England, while Oxford required such an oath at matriculation (Prest 1996).

Striving in a law-bound, seemingly rational universe made success more thinkable, possibly more doable. That universe made its appearance only after 1700 and as a result largely of the achievements of Newtonian science" (Jacob 2000, p277). It was Unitarians, above others, for whom the implications of Newtonian science and method provided a religious incentive system conducive to innovation and industrialisation. Unitarianism made getting rich from the Industrial Revolution morally acceptable. As Jacob argues "Unitarianism based upon science possessed a self-awareness that naturalized and made acceptable, even socially benevolent, what might have been construed, then and now, as greed and rapaciousness (Jacob 2000, p292). Or similarly, as Orange remarked with respect to the picture in Newcastle, "Among the Unitarians, Britain's industrial revolution was taking place not behind God's back but at his express command" (Orange 1983).

The Unitarian link to entrepreneurialism during the British Industrial Revolution can be seen in the occupational destinations of former students at Unitarian dissenting academies. Parker shows that of the 393 students educated at the Rational Dissenting and Unitarian, Warrington Academy between 1757 and 1782, at which Priestley taught, 98 entered for a training in 'commerce' compared with 22 in law, 52 in divinity and 24 in medicine (Parker 1914). This is in stark contrast to the graduates of English universities. Crafts states that he has failed to find even one graduate of Cambridge University before 1850 that went into manufacturing (Crafts 2009).

Science as a Strategic Political Asset: The Scientific Revolution's impact on religion in England was matched by its impact on politics. The Church of England was intrinsic to the state apparatus and, as such, the Latitudinarian moderate Enlightenment – the appropriation of science as an establishment bulwark against radicalism – was motivated more by politics than religion itself. Thomas Sprat's History of the Royal Society of London, written in 1667, explained how he and the other founders of the Royal Society had intended to pit Baconian philosophy against the sectarian conflict that they saw as the root of the English Civil War, and to diffuse the radical sects that had emerged during the Interregnum, and the associated suppression of the Anglican Episcopy, during the previous decade.

Jacob argues that one of the primary reasons for the triumph of Newton's mechanical system was its adoption as a strategic political asset by Anglican Latitudinarian churchmen in the late seventeenth and early eighteenth century. Newton's concept of a law-governed stable universe, regulated by God, was the ideal allegory for the advocacy of a stable and pious society (Jacob 1976). The culmination of this rhetoric was John Theophilus Desaguliers' *The Newtonian System of the World: the Best Form of Government*, published in 1728, which defended the Anglican political status quo.

The establishment also recognised the potential for science to act as antagonist if it was captured by radical political interests. Indeed, Jacob shows how Newton's science was combined with Spinoza and Hobbes to produce Republicanism. These views were incubated in the Dutch Republic in the early eighteenth century before spreading to France prior to the Revolution (Jacob 1981). The British establishment was suspicious of KAIs, particularly during periods of heightened political tension. Following the American War of Independence and the French Revolution public lecturers in England were treated suspiciously by the government. The government passed the Seditious Meetings Acts of 1795 and 1799 and KAIs were monitored for radical sympathies. Priestley, who was forced to flee to America in 1794 after his home in Birmingham was burned down in 1791 because of his support for Republicanism, remarked "The English hierarchy has reason to tremble even at an air pump or an electrical machine" (Delbourgo 2006).

In the nineteenth century, mechanics institutes were feared by the upper classes as potential hotbeds of radicalism. Shapin and Barnes argue that in response the upper classes sought to use mechanics institutes as tools of manipulation to subdue the working classes in the evenings and distract them from ideas of reform (Shapin & Barnes 1977).

Science as a Social Status Symbol: Royal patronage financed the careers of many of the natural philosophers who constituted Europe's 'Republic of Letters' from the beginning of the sixteenth century. Paul David (2014) and Joel Mokyr (2016) have stressed the importance of this patronage for the expansion of the scientific community during the Scientific Revolution and its adoption of the 'scientific norms' of open publication, peer evaluation and reputational reward for publishing priority. These norms stood in opposition to the prevailing norms of state secrecy and the appropriation of knowledge for economic or military advantage.

Natural philosophers conferred status upon European royals during the Scientific Revolution. By the late eighteenth century, science had also become a status symbol among the ruled. As Arnold Thackery has argued, it served particularly well the 'marginal men' of northern industry, wealthy but far away from the national status-conferring institutions based in London, and often marginalised by their religious non-conformism. Thackery refers to this phenomenon as the ‘Manchester Model’ and illustrates its importance to the Manchester Literary and Philosophical Society, Unitarians playing a major role in the society and embodying the image of the marginal man (Thackery 1974). Although Thackery stressed the idiosyncrasy of the Mancunian case, Shapin identified the same utility of science in relation to the founding of the Pottery Philosophical Society (Shapin 1972) and Inkster for the Sheffield scientific community (Inkster 1977).

Science as Entertainment: The Lunar Society, whose short list of members included Erasmus Darwin, James Watt, Mathew Boulton, Josiah Wedgewood and Joseph Priestley, met in Birmingham from 1765. Darwin described these meetings as the gathering of friends for “a little philosophical laughing”. The fun-loving sociability of the ‘Lunaticks’, as documented by Uglow (2003), featured throughout the KAI community. Simon Schaffer has illustrated the role of entertainment as a source of demand for scientific lecturers and institutions (Schaffer 1983). The eighteenth century witnessed the ‘commercialisation of leisure’, and natural philosophers competed in the marketplace. Experiments with electricity proved particularly popular, electrical philosophers taking centre-stage in the 1740s, particularly following the invention of the Leyden Jar in Germany in 1745, which aided the transportation of electrical power. As the *Gentleman’s Magazine* reported in 1745[63]:

> “From the year 1743, they discover’d phenomena so surprising as to awaken the indolent curiosity of the public, the ladies and the people of quality, who never regard natural philosophy but when it works miracles. Electricity became the subject in vogue, prices were willing to see this new fire, which a man had produced from himself…What astonishing discoveries have been made within these four years; The polypus on the one hand, as incredible as a prodigy, and the electric fire, as surprising as a miracle.”

The popular attractions of electrical shows were manifold. First, they were daring and dangerous. The French electrical philosopher Mazeas wrote of “that Wonderful Matter which Nature has kept hid from us since the Creation of the World. The fable of Prometheus is verify’d – what after this can mortals find difficult?” The *Gentleman’s Magazine* commented in similar terms on the accidental death during a performance of Russian electrical philosopher Richmann, “we are come at last to touch the celestial fire, which if we make too free with, as

[63] As quoted in Schaffer (1983).

it is fabled Prometheus did of old, like him we may be brought too late to repent of our temerity" (Schaffer 1983).

Second, a post-Newtonian public, versed from the 1710s onwards by early Newtonian public philosophers such as Desaguliers and by Clarke's Latitudinarian interpretation of Newtonian science, understood the significance of electrical current as a possible proof of the existence of God. Newton himself had identified God's presence in the forces of attraction and repulsion that he had discovered (Jacob and Stewart 2004). As Bristol cleric Richard Symes put it, commenting on an electrical orrery, "here a man will naturally ask himself, what is the power that puts bodies in motion, and what if the Light that illuminates them? The hidden powers of Nature are the cause which is clearly shewn by this Experiment and made more easy to be comprehended" (Schaffer 1983).

The 2008 edited volume *Science and Spectacle in the European Enlightenment* added grist to Schaffer's mill through case studies on theatrically performed chemistry lectures in the heart of the Parisian theatre district in the late eighteenth century (Lehman 2008), popularized physics in eighteenth century Paris (Lynn 2008), the amusements of eighteenth century pneumatics (Riskin 2008), and German itinerant lecturers of popular Enlightenment science (Bertucci 2008). The epitome of scientific entertainment during the Enlightenment, however, was probably Humphry Davy's lectures at the Royal Institution in London's Mayfair between 1801 and 1813. Although the Royal Institution's mission was primarily to educate rather than to entertain, Davy's charisma attracted large audiences of the rich and fashionable. An entertainment premium for scientific performance is hinted at by considering the differential between Davy's salary as lecturer at the Institution and that of his successor William Thomas Brande. Davy's annual salary reached £500, while the 'featureless' Brande who took over from Davy in 1813 was paid 'only' £200 (Hays 1983).

The possibility of an entertainment premium gave rise to problems concerning the dumbing-down of science and charlatanry. French lecturer Nollet described the pitfalls in striking the delicate balance of "spectacles of pure amusement" on the one hand and "too serious a study" on the other (Riskin 2008). Populist lecturer Benjamin Martin in the 1740s notes a critique he received from John Freke, another lecturer: "there are many empirical and ignorant pretenders gone out who obtrude themselves and their apparatus on the good-natured and generous part of mankind…Thus is the noble science brought into contempt and dispute" and that “all who shew any arts to new customers for profit are bound to try any means to get applause” (Schaffer 1983). These problems provided a role for institutionalised popular science as an authentication mechanism and KAIs filled that role. During the second half of the eighteenth century, scientific lectures began to take place predominantly within KAIs, as opposed to more diverse venues under the prevailing itinerant lecturing system, and by the second quarter of the nineteenth century the transition was largely complete.

Hays summarises the London case between 1800 and 1850, supplementing Schaffer’s eighteenth century analysis and Inskter’s provincial analysis between 1750 and 1850. He concludes that performing for audiences that wished to be entertained was an important source of the patronage for a scientific career during this era (Hays 1983, Inkster 1980).

KAIs and Rational Dissent: An Empirical Analysis

Given the Enlightenment subsidies listed above, Rational Dissenters should have exhibited a particularly strong demand for KAIs, operating through the ‘science as theology’, ‘science as strategic political asset’ and ‘science as social status’ channels. As such, a statistical correlation between Rational Dissent and KAI prevalence, after controlling for confounding variables, could reflect these subsidies. On this basis, in this final section of the chapter I provide falsifiable empirical evidence of part of the Enlightenment subsidy to KAIs by illustrating a link between the geographical prevalence of Rational Dissent and that of the emergence of KAIs in England prior to and during the British Industrial Revolution.

I have compiled data on the locations of all dissenting congregations in England in the early eighteenth century, marking those that were to become denominationally Unitarian (and hence explicitly identifiable as Rational Dissenters) over the course of the following century. Using this data, I compare a geographical measure of the local prevalence of Rational Dissent across early eighteenth century England with the pattern of the emergence of KAIs in England between the early eighteenth and mid-nineteenth centuries. The basic test of the relationship is the question: did locales with Rational Dissent in the early eighteenth century tend to adopt KAIs sooner than those without?

The main challenge for identification is the potential endogeneity of Rational Dissent to industrialisation. The strategy to overcoming this challenge has three elements. The first is to take the spatial distribution of Rational Dissent prior to the Industrial Revolution to reduce the chance of reverse causality. The second is to control for standard factors that influence the spatial distribution of any economic or cultural phenomenon, namely population and population density. The third element is more complicated. One must control for any economic mechanisms that might also lie behind Rational Dissenters' heightened demand for KAIs. By economic mechanisms, I refer to profitmaking incentives for Rational Dissenters to engage in science and KAIs as opposed to cultural, theological or political incentives. If present, such a mechanism would confound the identification of the Rational Dissent Enlightenment subsidy for KAIs.

Until well into the nineteenth century, Rational Dissenters were legally discriminated against in certain parts of the labour market. The Corporation Act (1661) and the Test Act (1673) decreed that holders of municipal office, i.e. members of the governing bodies of incorporated boroughs and anyone holding 'offices of trust' under the Crown, whether civil or military, must receive holy communion under the rites of the Church of England. Furthermore, the Blasphemy Act (1698) barred any denier of the doctrine of the Trinity from holding any public office (Prest 1996). As a result, Rational Dissenters may have been particularly incentivised to pursue industrial careers, possibly resulting in a particularly high demand for KAIs as R&D institutions. This would provide an interesting example of a positive 'allocation of talent' mechanism operating on economic growth, i.e. where talent is exogenously re-directed away from rent-seeking towards value-creating activities (Murphy, Shleifer & Vishney 1991, Hsieh et al 2013). However, for the present identification challenge, the possibility necessitates an identification strategy based on an exogenous source of variation in the prevalence of Rational Dissent.

In 1715, to map the dissenting vote for lobbying purposes, Dr John Evans, a leading dissenting minister, compiled a census of dissenting congregations across England and Wales. He recorded the denomination of each congregation in terms of the three denominations of English 'Old Dissent': Presbyterian, Congregationalist and Baptist (General and Anabaptist), the size of each congregation and the number of eligible voters. In 1729, he updated the census to include all new congregations established during the interim. By referring to the original manuscript,[64] I construct counts of dissenters and congregations by each denomination for each English 'hundred', an historical English administrative unit.

Dr Evans' census can help statistically identify congregations that practiced Rational Dissent and provide a control group of those that did not. However, prior to the establishment of Unitarianism as a formal denomination in 1774, Rational Dissent was a denominationally ambiguous practice. As stated above, Unitarianism drew most strongly from the English Presbyterians, but not all English Presbyterians converted, nor was it exclusively Presbyterian.

The relative tendencies of the different denominations of Old Dissent to practice Rational Dissent in the early eighteenth century is illustrated the 'Salter's Hall controversy' of 1719, a pivotal event in the history of Rational Dissent (Wykes 2009). This was a tumultuous debate between leading dissenting ministers concerning whether they should collectively subscribe to the first article of the Church of England – the acceptance of the doctrine of the Trinity. The debate took place under intimidation by Parliament in the context of the Occasional Conformity Act of 1711, which forbade dissenters from circumventing aspects of the Clarendon Code and related statutes by occasionally taking Anglican Communion (Wykes 2009). The motivations of those who refused to subscribe bore the unmistakable marks of Rational Dissent: rejection of the Trinity on doctrinal grounds, as the Trinity was not supported by scripture nor reason, and the objection to encroachment upon Christian liberty, in being pressurised to subscribe. Indeed, the controversy did much to promote Rational Dissent and the contemporary texts setting out the nontrinitarian position, such as of Samuel Clarke's *Scripture Doctrine of the Trinity* of 1712 and John Locke's *Paraphrase and Notes on the Epistles of St Paul* of 1707.

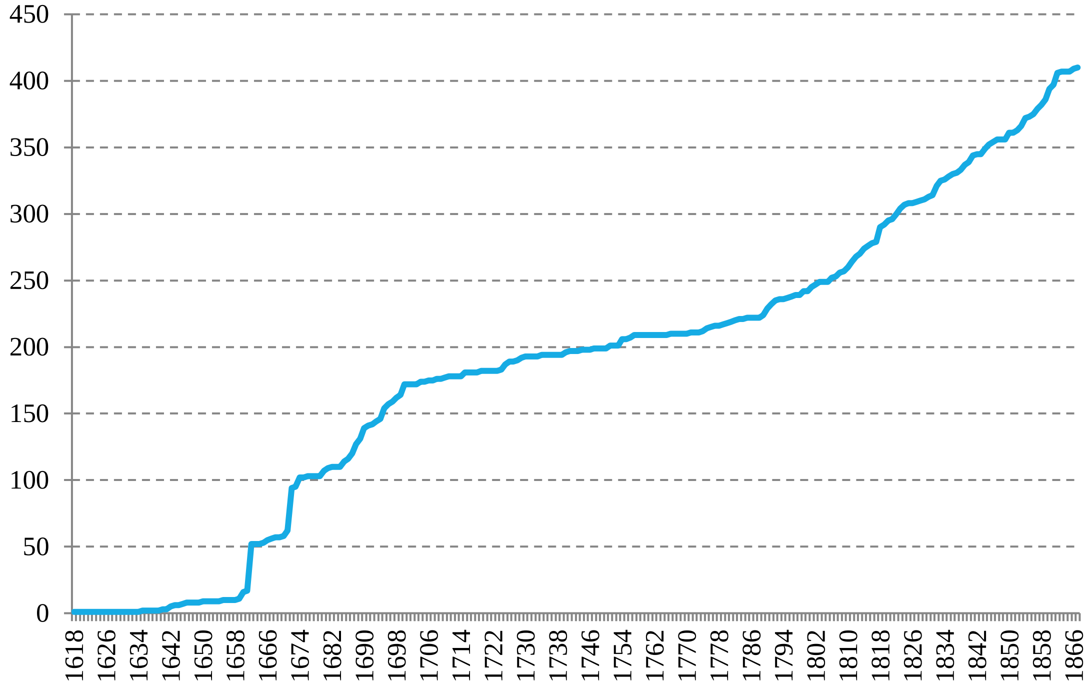
Overall, there were 78 subscribers to the first article of the Church of England and 73 non-subscribers. Of the 76 Presbyterians embroiled, 27 subscribed, while 49 did not, indicating a clear bias towards Rational Dissenting values. Indeed, several subscribing Presbyterians later renounced their subscription. The General Baptists too displayed a clear bias towards Rational Dissent, with only 1 subscriber and 12 non-subscribers. The other two denominations exhibited a bias towards doctrinal orthodoxy and/or compliance with Church. Of the 39 Independents,

[64] Access to which was kindly granted by Dr David Wykes at Dr Williams' Library in London.

31 subscribed while 8 did not and of the Particular Baptists, 11 subscribed while 2 did not[65] (Wykes 2009).

I match the dataset on Old Dissent based on Evans' 1715/1729 census with a dataset of the founding dates and locations of all Unitarian congregations in historical existence in England. This is based on a list compiled heroically by Unitarian scholar Alan Ruston over the course of fifty years of research. The dates of congregational foundation in Ruston's list do not necessarily represent the dates on which each congregation became denominationally Unitarian. Only in the case of new Unitarian congregations established post-1774 is this so. However, Ruston's list enables one to identify which of the congregations listed in the Evans census went on to become Unitarian. This means that one can identify for the early eighteenth century the union of active Rational Dissenting congregations and the congregational sources of Rational Dissent. Even in the latter case, a congregation that went on to become Unitarian is likely to have been more predisposed to Rational Dissent in 1729 than one that did not, however latent that predisposition may still have been at that time.

Figure 4.5: Congregations founded in England that would eventually become formally Unitarian



[65] These figures do not add up to the total of the 151 ministers involved as the records are uncertain as to the denominations of a small number of the ministers.

Figure 4.5 shows the time series of the number of congregations in existence each year from 1620 onwards that would eventually become denominationally Unitarian. One can see the initial surge from essentially zero following the Act of Uniformity in 1662, which maintained momentum until the end of the seventeenth century. By 1729, the year of the augmented version of the Evans census, there were 192 such congregations in existence in England. Thereafter, this number remained quite steady up until the founding of denominational Unitarianism in 1774, reaching only 211 by 1773, after which it experienced another leg of growth, rising to around 400 by the mid-nineteenth century. The snapshot of early eighteenth century Rational Dissent identified by this methodology captures a pre-Industrial Revolution and largely pre-KAI pattern of Rational Dissent, which helps to reduce the potential endogeneity of Rational Dissent to industrialisation or KAIs. The congregational time series also tells one that this snapshot represents a significant portion of the overall picture of Rational Dissent that had emerged by the nineteenth century (half of it, on a congregational basis).

By matching the Evans and Ruston datasets I code each English hundred by its dissenting status in 1729. The three dissenting statuses are: Rational Dissent, non-Rational dissent, and no dissent, and the results are shown geographically in figure 4.6. Next, using the KAI dataset introduced in chapter 2, I code each English hundred for the year in which its first KAI was established. This enables the examination of whether hundreds with Rational Dissent in 1729 tended to adopt KAIs sooner than those without.

Given the dynamic nature of the dependent variable – each hundred's KAI status over time – the technique of 'survival analysis' presents a useful empirical framework. Survival analysis is used in medicine to estimate the probability of patient survival over time following a diagnosis, taking into consideration patient characteristics and treatments[66]. Cleves et al (2007) provides a comprehensive introduction to survival analysis, and Bogart (2007) uses it in an economic history context to investigate the diffusion of the turnpike network in eighteenth century Britain. In the present case, the unit of analysis is the English hundred, and the event signifying the year of 'non-survival' for each hundred is the year of adoption of its first KAI.

[66] Previous economic applications of survival analysis include the study questions concerning bank failures during financial crises (i.e. which bank characteristics determine duration of survival following a systemic shock?) (e.g. Evrensel 2008).

Figure 4.6: English Dissent in 1729, by English hundreds

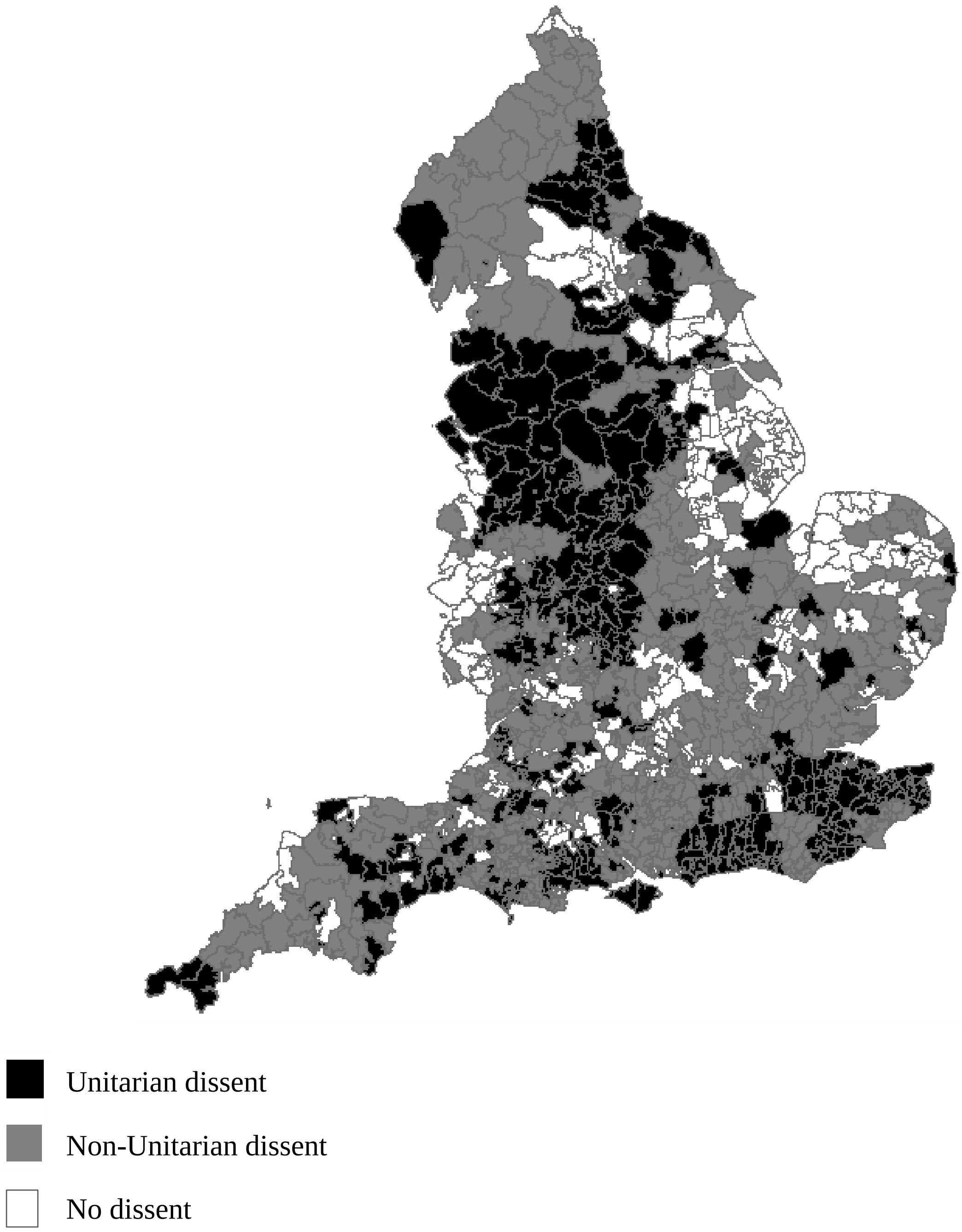
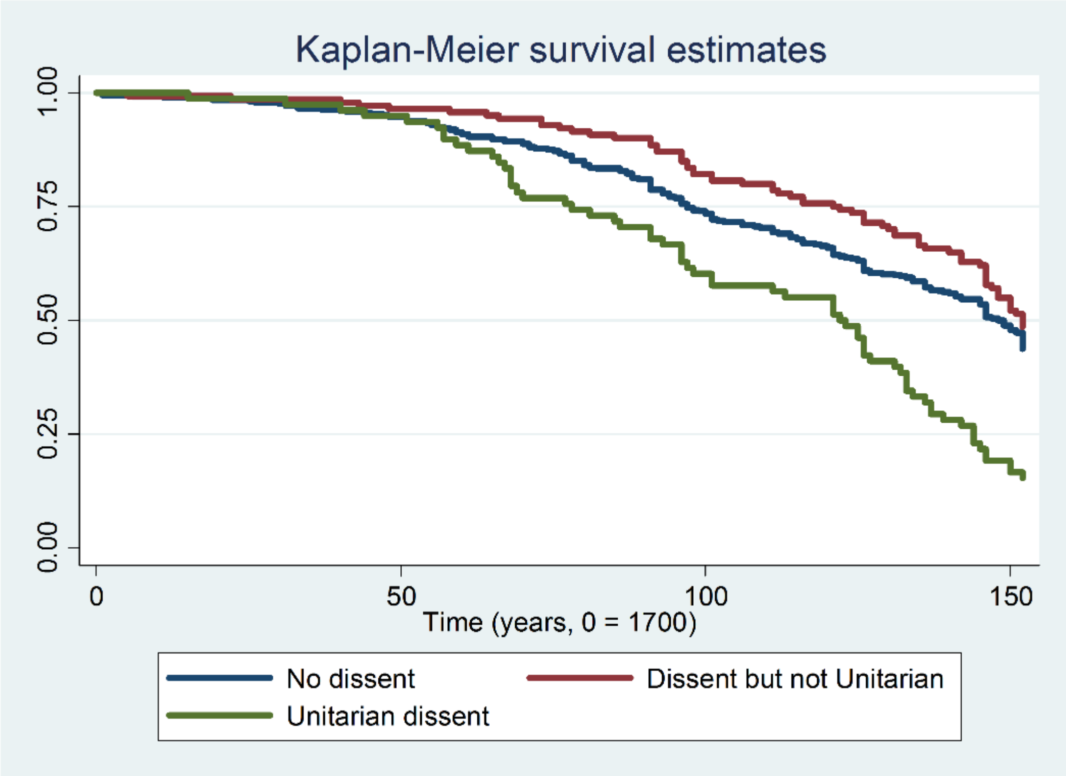


Figure 4.7: Kaplan-Meier survival rates for learned society adoption by English hundreds (districts), by dissenting status in 1729



The first step of the analysis is to estimate Kaplan-Meier survival curves showing the proportion of English hundreds without a KAI at time *t*, starting in 1700. The hundreds are stratified into three groups reflecting the three dissenting statuses described above, so there are three curves. The *i*'th curve traces the proportion of hundreds within group *i* that does not yet have a KAI by year *t*. Figure 4.7 shows the result. The two non-Rational Dissenting groups have similar curves, and indeed are not statistically distinguishable from one another using 95% confidence intervals. In fact, of the two groups, the non-dissenting hundreds tended to adopt KAIs earlier than the non-Rational dissenting hundreds. However, there is a marked difference between these two groups and the Rational Dissenting group, which adopted KAIs significantly earlier, suggesting a 'Rational Dissenting effect'.

The next step in the analysis is to estimate the size of this Rational Dissenting effect on the year of KAI adoption, while at the same time controlling for confounding variables. Specifically, it is important to model adoption across space as a dynamic process controlling for the concurrent growth of local population, the overall growth of KAIs at the national level and the influence of neighbouring hundreds. I choose a standard discrete-time logistic hazard function to model the probability of adoption in a hundred over time as a function of its characteristics[67]. I include as covariates, in addition to binary variables reflecting non-Unitarian dissent and Unitarian dissent[68], the log population of hundred *i* on year *t*, and the number of KAIs within a 20km radius of hundred *i* in year *t-1*. The first year of observation is 1750, due to the lack of availability of population data by hundred before this year, and the last year is 1851[69]. Hence, the following model is estimated, with standard errors clustered by English hundred:

$$log\left(\frac{\lambda(t \mid x_{it})}{1-\lambda(t \mid x_{it})}\right) = \beta_1 DISSENT\_NOT\_UNITARIAN_i + \beta_2 UNITARIAN\_DISSENT_i + \beta_3 LnPop_{it} + \beta_4 NEIGHBOUR\_LS_{it-1} + \beta_5 Ln(t)_t \qquad (1)$$

where λ(t) is the hazard function, which describes the probability that a hundred will adopt a KAI in year *t* if it has not already done so, and the final term on the right-hand side is the baseline hazard function, which increases log-linearly as a function of time[70].

Results: Dissent and KAIs

The results are reported in table 4.2 as odds-ratios, which indicate the marginal increase in the probability of adoption of a KAI conditional on a marginal increase in each explanatory variable (or of a switch from 0 to 1 in the binary case). In contrast to the simple Kaplan-Meier curve, hundreds with non-Rational dissent are now associated with faster adoption than those with no dissent, being 2.1 times more likely to adopt in any year. Rational Dissent retains its strength as a predictor of adoption in any year, a Rational Dissenting hundred being 3.7 times more likely to adopt than one with no dissent and 1.7 times more likely than one with non-Rational dissent[71]. The differences in adoption probability between the three categories are statistically significant. Figure 4.8 displays model-predicted survival curves by dissenting status, conditional on the covariates in the regression. The faster adoption rate of Rational Dissenting hundreds than hundreds with non-Rational dissent can be clearly seen.

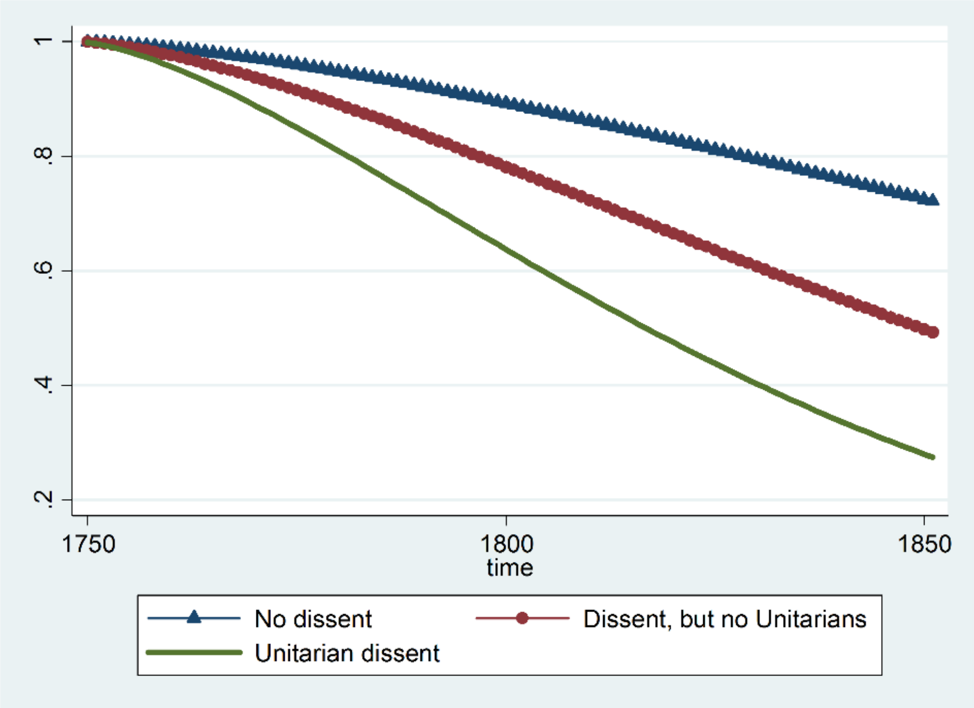
[67] This is the most commonly used discrete time hazard model in the literature, see Singer and Willet (2003).
[68] 'No-dissent' is chosen as the reference, hence no dummy variable is included.
[69] As a result I am forced to omit the hundreds that adopted a learned society before 1750, of which there are only a handful.
[70] which is chosen due to the constant log-linear aggregate growth rate of the number of KAIs between 1750 and 1850.
[71] (=3.66/2.13)

Table 4.2: results of survival analysis of adoption of learned societies by English hundreds.

Dependent variable: *Adoption of learned society*	Marginal odds-ratio
Non-Unitarian Dissent	2.13***
	(4.58)
Unitarian Dissent	3.66***
	(6.79)
Ln Population	1.82***
	(8.37)
Learned Society within 20km	1.01
	(1.46)
Baseline hazard (log of time)	1.70***
	(4.97)
Hundreds (districts)	572
Periods at risk	44,570

Discrete-time logistic harzard function. Baseline hazard is log of time.
t statistics in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Standard errors clustered by hundred.

Figure 4.8: Predicted survival curves for learned society adoption, for i)Unitarian-dissenting, by dissenting status in 1729



The 'Five Mile Act' of 1665 as an Instrument for Rational Dissent

To further control for the endogeneity of Rational Dissent to economic factors, I attempt to isolate an exogenous source of variation in Rational Dissent across England due to the impact of the Five Mile Act of 1665, which restricted the locations in which dissenting ministers could preach. As mentioned above, Charles II instituted the Five Mile Act in the 1660s as part of the Clarendon Code, in the context of the post-Restoration political and religious tension. The Five Mile Act declared it illegal for anyone to preach within five miles of any city, corporate town or borough sending members to parliament without having taken the oath of allegiance to the articles of the Church of England required under the Act of Conformity. It also barred any minister failing to conform from preaching within five miles of any parish in which they had previously worked. Figure 4.9 displays the exact wording of the statute.

Figure 4.9: The Five Mile Act 1665

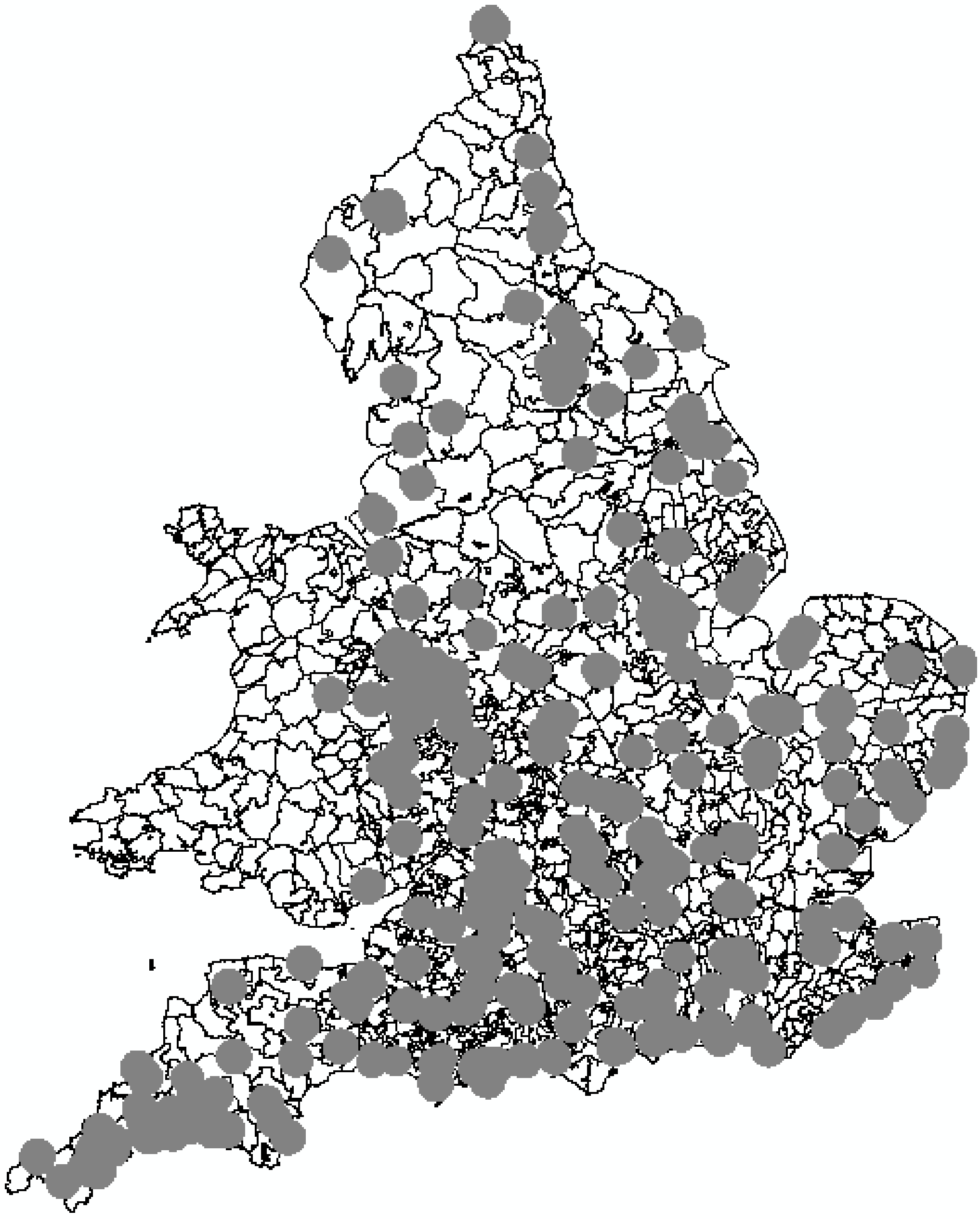
Persons preaching in Conventicles not to come within Five Miles of any Corporation sending Members to Parliament before they have taken the said Oath.

And all such person and persons as shall take upon them to preach in any unlawfull Assembly Conventicle or Meeting under colour or pretence of any Exercise of Religion contrary to the Lawes and Statutes of this Kingdome shall not at any time from and after the Fower and twentyeth day of March which shall be in this present yeare of our Lord God One thousand six hundred sixty and five unlesse onely in passeing upon the Road come or be within Five miles of any Citty or Towne Corporate or Burrough that sends Burgesses to the Parlyament within His Majesties Kingdome of England Principallitie of Wales or of the Towne of Berwicke upon Tweede or within Five miles of any Parish Towne or Place wherein he or they have since the Act of Oblivion beene Parson Viccar Curate Stipendary or Lecturer or taken upon them to preach in any unlawfull Assembly Conventicle or Meeting under colour or pretence of any Exercise of Religion contrary to the Lawes and Statutes of this Kingdome before he or they have taken and subscribed the Oath aforesaid before the Justices of Peace at their Quarter Sessions to be holden for the County Rideing or Division next unto the said Corporation Citty or Burrough Parish Place or Towne in open Court (which said Oath the said Justices are hereby impowered there to administer) upon forfeiture of every such offence the summe of Forty pounds of lawfull English money, the one Third part thereof to His Majestie and His Successors, the other Third part to the use of the poore of the Parish where the offence shall be committed and the other Third part thereof to such person or persons as shall or will sue for the same by Action of Debt Plaint Bill or Information in any Court of Record at Westminster or before any Justices of Assize Oyer and Terminer or Goale delivery or before any Justices of the Countyes Pallatine of Chester Lancaster or Durham or the Justices of the Great Sessions in Wales or before any Justices of Peace in their Quarter Sessions wherein noe Essoigne Protection or Wager of Law shall be allowed.

Fine: £40

The Act had a long legacy on the geographic distribution of dissent in England. While dissenters engaged in 'occasional conformity' and worshipped in secret, many dissenting ministers and teachers re-located to parts of country that did not send members to parliament. Figure 4.10 shows the areas in England where nonconformist worship was forbidden after 1665. I have constructed this map by coding five mile radiuses around all cities, county towns and boroughs in 1665. The south and south-west of the country was covered most densely, while the north and midlands were less covered. The spatial distinction created by the Act between areas where Rational Dissenters could and could not preach is a useful source of exogenous variation in Rational Dissent. First, it pushes back part of the spatial determination of Rational Dissent to the seventeenth century, even further before the Industrial Revolution began. Second, it is the result of an exogenous state policy unrelated to industrialisation.

Figure 4.10: Shaded Area is Land Area of England Covered by the Five-Mile Act of 1665



I calculate a 'Five Mile Act' variable for each hundred in the dissenting status and KAI dataset used above. I take the area of hundred *i* in km sq covered by the Act and calculate the overall area of hundred *i* as a control. These variables are then used together to instrument the presence of Rational Dissent in hundred *i* in 1729. To do so, I estimate the following two-stage least squares equations:

Stage 1 Equation

$$RATIONAL\_DISSENT_i = \alpha + \beta_1 FIVE\_MILE\_ACT\_AREA_i + \beta_2 TOTAL\_AREA_i + \beta_3 LnPOP_i + \beta_4 DISSENT\_DUMMY_i + \beta_5 FIVE\_MILE\_ACT\_DUMMY_i + \delta + \varepsilon_i$$

Stage 2 Equation

$$TIME\ TO\ FIRST\ KAI_i = \alpha + \beta_1 \widehat{RATIONAL\_DISSENT}_i + \beta_2 LnPOP_i + \beta_3 DISSENT\_DUMMY_i + \beta_4 FIVE\_MILE\_ACT\_DUMMY_i + \delta + \mu_i$$

In the first stage, the Rational Dissent dummy is regressed on the Five Mile Act area and total area variables, controlling for population in 1761, the presence of any dissent at all and county fixed-effects. In the second stage, the time to the adoption of hundred *i*'s first KAI in years from 1750 is regressed on the IV for Rational Dissenting status from the first stage, along with the same covariates from the first stage.

The results of this two-stage least squares procedure are shown in table 4.3. The estimated impact of this exogenous source of Rational Dissent on KAI adoption is that a Rational Dissenting hundred is likely to have adopted a KAI 46 years earlier than a non-Rational Dissenting hundred. This supports the findings of the survival analysis and the interpretation of a cultural effect of Rational Dissent on KAIs.

Table 4.3: IV estimation of Year of First Knowledge Access Institution as a function of Unitarianism, where Unitarianism is instrumented by the Five Mile Act 1665

	(1) *IV estimation*	(2) *IV estimation*
Second-Stage for Year of First KAI		
Rational Dissent Dummy	-45.63**	-48.11**
	(20.46)	(20.64)
Dummy for Any Dissent	-6.190	-5.731
	(5.380)	(5.357)
Ln(Population in 1761)	-5.075**	-4.863***
	(2.573)	(2.594)
Five Mile Act Dummy		0.266
		(4.620)
County FE	Yes	Yes
N	600	599
R^2	0.241	0.225
First Stage for Rational Dissent Dummy		
Area covered by Five Mile Act (km^2)	-0.00028	-0.00034
	(0.00022)	(0.00023)
Area (km^2)	-0.00035*	-0.00034*
	(0.00011)	(0.00011)
Dummy for Any Dissent	0.192*	0.192*
	(0.0409)	(0.0406)
Ln(Population in 1761)	0.155*	0.157*
	(0.0283)	(0.0286)
Five Mile Act Dummy		0.0666
		(0.0608)
County FE	Yes	Yes
N	600	599
R^2	0.311	0.313

Standard errors clustered at county level in parentheses. *** $p < 0.10$, ** $p < 0.05$, * $p < 0.01$

Conclusion

This chapter has argued that Britain's eighteenth and nineteenth century Knowledge Access Institutions were not endogenous to the British Industrial Revolution. First, profitmaking incentives do a poor job of inducing innovative effort even when the underlying conditions are relatively conducive. To claim that innovative effort and investment in KAIs during the British Industrial Revolution were endogenous asks too much of the incentives to innovate in eighteenth and nineteenth century Britain.

Second, the demand for science and KAIs in eighteenth and early nineteenth century Britain was multifaceted, much of it based on cultural rather than economic motives. Under the influence of the European Enlightenment, Britain built KAIs in response to the demand for science as progressive ideology, entertainment, social status symbol for wealthy establishment outsiders and strategic political and religious asset, alongside the demand for R&D productivity. The Enlightenment subsidies to which these utilities gave rise made an eighteenth and nineteenth century career in science pay and helped pay for the construction and operating costs of the world's first R&D infrastructure. The relationship between Britain's KAIs and technological innovation during the British Industrial Revolution identified in chapter 3 should be interpreted as causal.

Chapter 5

The Railway Transport Revolution and Access to Knowledge in the Late Nineteenth Century

Did Knowledge Access Institutions (KAIs) facilitate the emergence of modern economic growth outside of Britain? Was technological innovation in the industrialising countries of the late nineteenth century supported in a general sense by national infrastructures of KAIs? Indeed, can we explain Britain's lead by its precocious KAI infrastructure?

These questions follow naturally from the argument that British KAIs facilitated technological innovation during the British Industrial Revolution. Yet they are difficult to answer within this thesis because while the thesis is focused mostly on the British case they require a thorough comparative perspective. Moreover, such a comparison must take into account the qualitative differences that KAIs exhibited across countries, which may have affected their efficacy. For example, France's substantial KAI infrastructure was funded and operated by the state rather than by private individuals. Did this reduce the contribution to innovation of France's KAIs compared to that of Britain's KAIs? For example, did the French state tend to direct innovative effort towards sectors and projects that were less impactful on economic growth and did it inhibit the practical application of knowledge by standing in the way of commercialisation? Or, rather, were French KAIs perhaps more efficacious than their British counterparts? Did privileges awarded by the French government for technology developed within KAIs perhaps offer a better appropriation mechanism than the English patent system and the free market?

Although the comparative work necessary to tackle these questions is beyond the scope of this thesis, this chapter aims to make two related contributions. First, it illustrates the existence of a strong correlation between a simple measure of a country's core KAI infrastructure and its level of economic development in the late nineteenth century. Second, although no attempt is made to tackle the crucial question of the efficacy of KAIs outside of Britain, it investigates whether KAIs – in reducing the cost of access to knowledge – were at least pushing upon a binding global constraint to technological innovation in the late nineteenth century. KAIs were far from the only factor reducing knowledge access costs in countries around the world in the nineteenth century. By identifying variation in knowledge access costs due to other factors and examining its correlation with an indicator of the rate of technological innovation one can establish whether modern economic growth was responsive to falling knowledge access costs. If so, it follows that KAIs may have contributed to the emergence of modern economic growth in a wider context than in the British case alone.

KAIs and the ‘Convergence Club’

In 1876 a committee comprising the Academic Council of Harvard University, the Boston Public Library and the American Academy of Arts and Sciences produced an international catalogue of all known published scientific periodicals (Scudder 1879). Using this catalogue, one can construct national counts of scientific institutions with a publishing record, which can serve as a rough proxy for the size of national core KAI infrastructures. I denominate these counts by national populations in 1870 using data collected by Alex Klein and Stephen Broadberry (2011) and Angus Maddison (2009). Figure 5.1 shows core KAIs per million capita across 17 countries and country groups as they appear in the committee’s catalogue. In figure 5.2, I compare in the form of a scatter plot core KAIs per capita in 1876 with GDP per capita in 1913 (also taken from Broadberry and Klein 2011 and Maddison 2009), representing the pre-war apotheosis of the late nineteenth and early twentieth century ‘convergence club’. This relationship exhibits a very strong correlation of 0.9.

Next, I estimate a simple cross-country ‘beta-convergence’ model of core KAIs and economic growth in the late nineteenth and early twentieth centuries. I regress percentage growth in GDP per capita between 1870 and 1913 on KAIs per Capita in 1876 and initial GDP per capita in 1870. The results are shown in table 5.1. A one percent higher KAI to population ratio in 1876 is associated with 17ppts more cumulative growth between 1870 and 1913, with a robust standard error of 6ppts (significant at the 1% level). In standardised terms, a one standard deviation higher KAI to population ratio was associated with a 0.93 standard deviation higher growth rate. Figure 5.3 illustrates a scatterplot of the partial correlation between core KAIs per capita in 1876 and growth between 1870 and 1913, controlling for GDP per capita in 1870. The correlation coefficient is 0.5.

Figure 5.1: Core KAIs per Million Population 1876

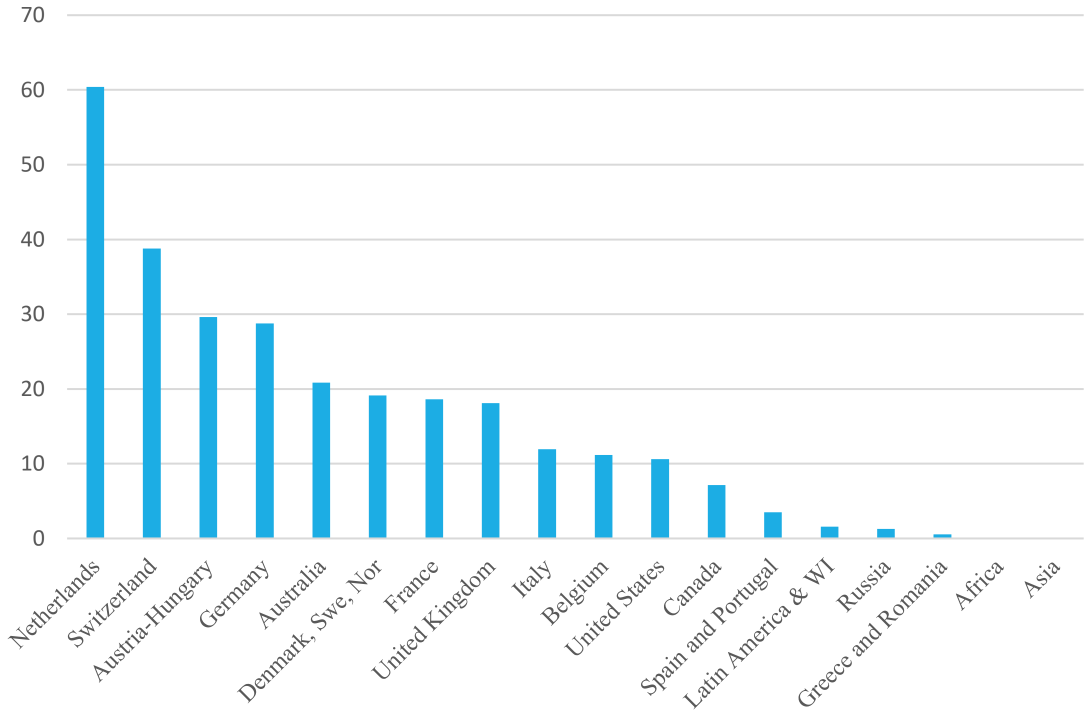


Figure 5.2: (Log) Core KAIs per Capita 1870 vs (Log) GDP per capita 1913 (Correlation coefficient = 0.9)

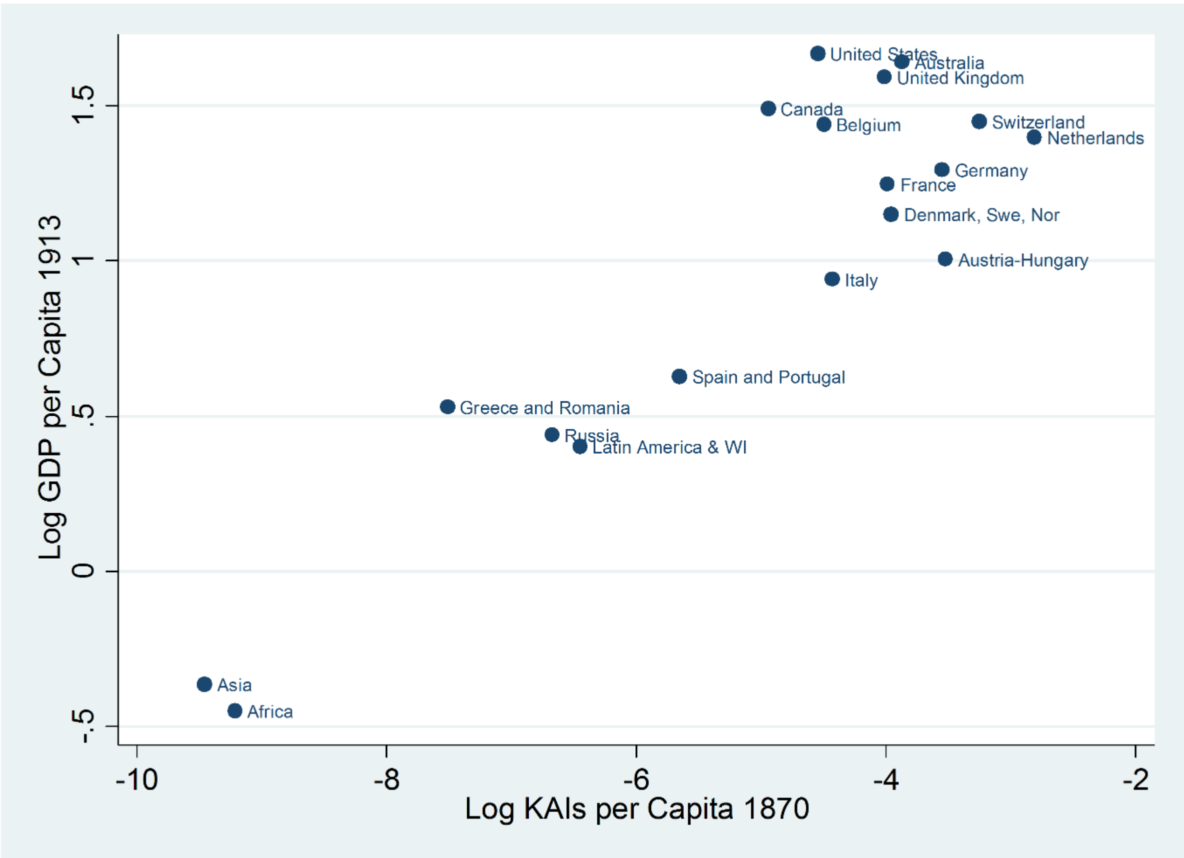
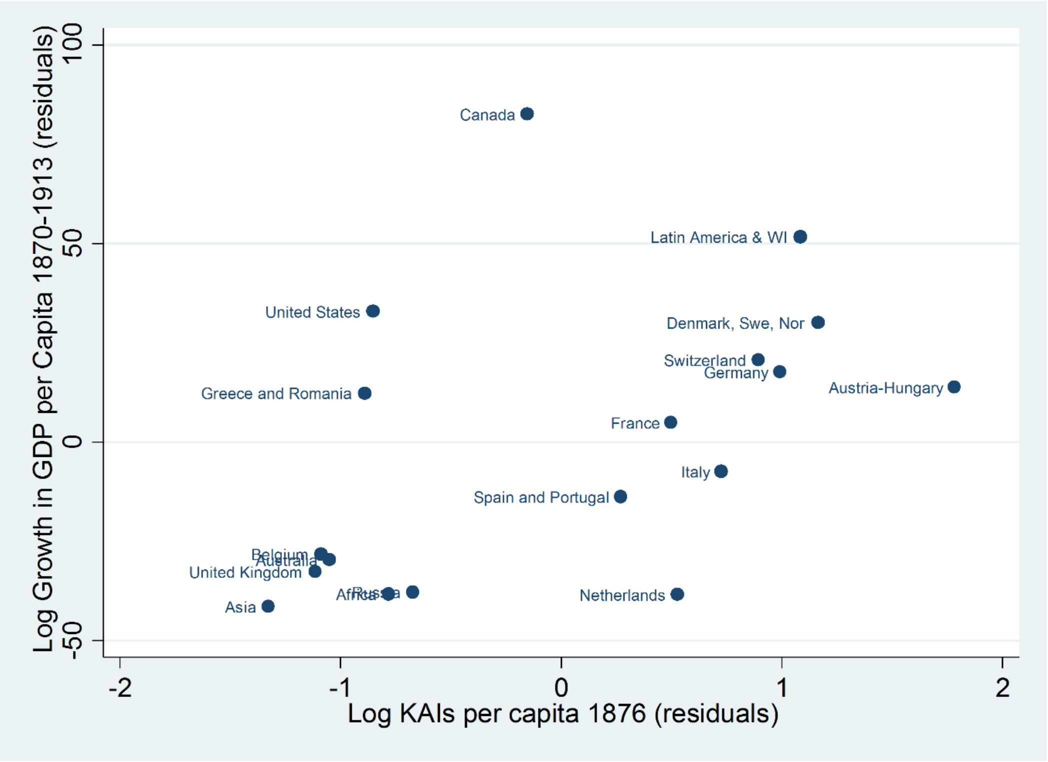


Table 5.1: "Beta-Convergence" Regression, KAIs and Growth 1870-1913

	(1) 100*% Growth of GDP per Capita, 1870-1913
(Ln) KAIs per Capita, 1876	17.07^{***} (5.71)
(Ln) Initial GDP per Capita, 1870	-39.59^{*} (21.26)
Constant	182.27^{***} (36.04)
Observations/Countries	18
R^2	0.247

Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Figure 5.3: GDP Growth 1870-1913 vs Log KAI per Capita 1870, partial correlation controlling for Log GDP per Capita in 1870 (Correlation coefficient = 0.47)



Clearly, this cross-country relationship between KAIs and economic growth in the late nineteenth and early twentieth centuries cannot be interpreted causally as it is subject to serious concerns about reverse causality and omitted variables. Nevertheless, the fact that countries with more-developed KAI infrastructures had more successful economies in the late nineteenth and early twentieth century means that KAIs pass a basic test of relevance to the global diffusion of modern economic growth and warrant further investigation as a causal factor.

Rail and Knowledge Access Costs

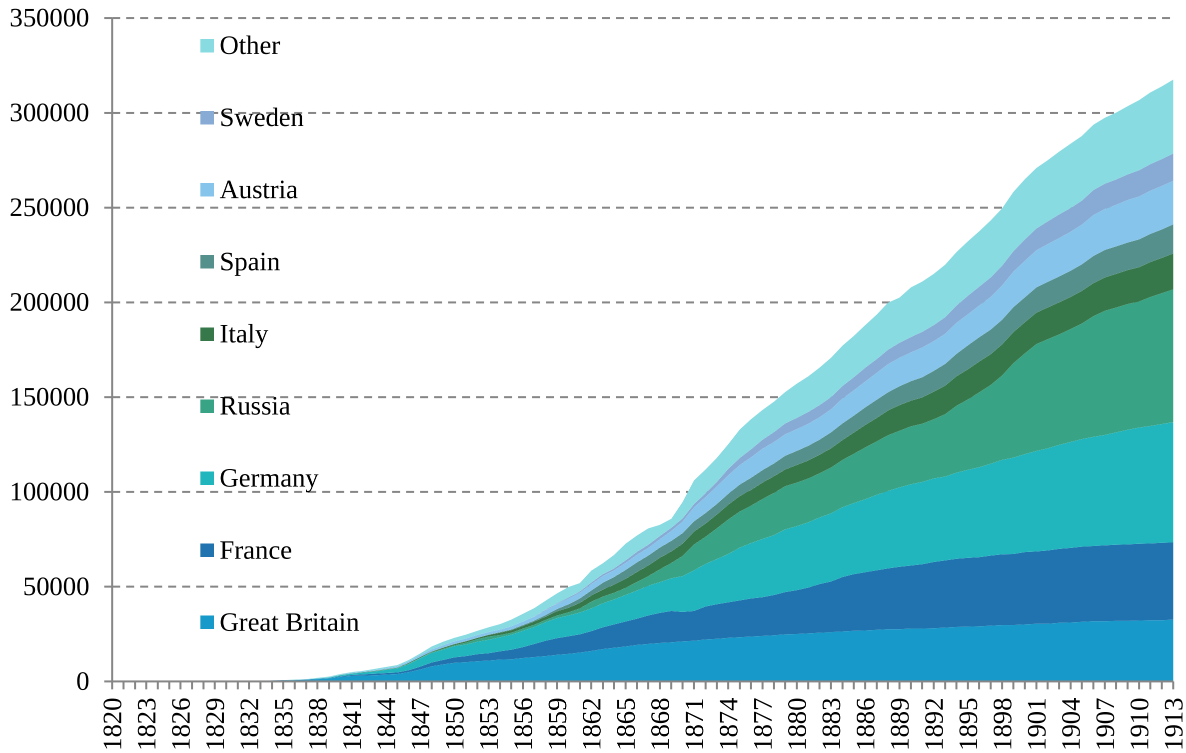
As discussed above, some of the basic characteristics of KAIs differed across countries, such as the state's level of financial and operational involvement. These differences may have influenced the relative efficacy of KAIs across countries, complicating the link between the size of the KAI infrastructure and its impact on knowledge access costs by country. Investigating the differences in efficacy of KAIs across countries is beyond the scope of this thesis, nevertheless, one can shed some light on whether KAIs might have influenced the emergence of modern economic growth more broadly than in the British case alone by asking whether by reducing knowledge access costs KAIs were at least pushing against a binding or non-binding global constraint.

We can test whether the knowledge access cost constraint was active or not for modern economic growth in the late nineteenth century by examining the correlation between knowledge access costs and an indicator of modern economic growth. Moreover, we can utilise variation in knowledge access costs due to any of its underlying sources, as opposed to variation due to KAIs alone. As such, below, I attempt to identify the impact on modern economic growth during the late nineteenth and early twentieth centuries of falling knowledge access costs due to the global rail transportation revolution. If modern growth was responsive to railways via the knowledge access channel, then it is likely that it would have been responsive also to efficacious KAIs.

Between 1825, when the first railway line built to carry passengers by steam locomotive was opened between Stockton and Darlington in Britain and the beginning of the First World

War, over 950,000 km of railway track were laid worldwide[72]. Figure 5.4 shows the growth of rail track across Europe prior to 1913. The last forty years or so of the period saw remarkable growth. In 1870 there were around 95,000km of track laid in Europe, most of it in Britain, Germany and France. By 1913 it had increased by 235% to around 318,000km. The movement of people along the rails increased at an even faster pace. The total number of passenger journeys per year in Europe rose from 670 million in 1870 to 5.1 billion in 1913, an increase of 770%.

Figure 5.4: Length of Rail Track Laid across Europe 1820-1913 (km)



The radically expanded set of opportunities for face-to-face communication to which mass rail transportation gave rise must have reduced knowledge access costs. This would be particularly so in the case of tacit, as opposed to codified, knowledge, which requires personal interaction for successful transmission. Tacit knowledge is thought to play a critical role in the process of technological innovation, raising the potential importance of the rail revolution to modern economic growth (Polanyi 1958, Cowan, David & Foray 2000, Howells 2002). But a substantial reduction in the cost of written correspondence due to the transportation of post by rail must have reduced the cost of access to codified knowledge too.

[72] Based on the sum of rail length of 34 countries with the largest rail networks.

The rail revolution occurred alongside two other components of a broader transport and communications revolution. The introduction of the steam propulsion of ships saw international freight rates decline by 50% and global shipping trade increase by around 400% between 1870 and 1913 (Jacks and Pendakur 2010). Meanwhile, the growth of the international telegraph network dramatically reduced the cost of both national and international remote communication. In 1837, the first commercial application of the electrical telegraph connected railway operatives between Euston and Camden Town stations in London. By 1898 the global telegraph network handled around one million messages a day across more than 100,000 offices around the world, sent along around three million miles of wire (Bryn 1900). Given these major concurrent developments in transportation and communication, and their likely impact on knowledge access costs, it may indeed not be a coincidence that modern economic growth accelerated in a broad set of countries during this period.

But can we measure the impact of the growth of railways on the rate of technological innovation? If so, can we distinguish the impact that it had through a reduction in knowledge access costs as opposed to market access costs (Sokoloff 1988)? Below, I attempt to do so on the basis of two empirical analyses. First, I examine the within-country link between rail density and patenting rates (a proxy for technological innovation) in 21 countries worldwide between 1883 and 1913, controlling for population, national income and the business cycle. To distinguish between knowledge and market access effects, I measure side-by-side the impact on patenting of both passenger numbers as a proxy for knowledge access, and freight volumes as a proxy for market access. Second, I examine within-state rail density and patenting in the United States between 1840 and 1890. To distinguish between the knowledge and market access effects in this setting I examine the effect of rail on the quality of patents as opposed to merely the quantity, measured by state-level scores of average forward-citation counts per patent. I argue that this helps to distinguish between knowledge and market access effects because patent quality is likely to be influenced by knowledge access costs but not market access costs. The results of these two analyses point to a large effect of rail on patenting via the knowledge access channel, supporting the claim knowledge access costs represented an active constraint to modern economic at the global level in the late nineteenth and early twentieth century. As such, if KAIs reduced knowledge access costs outside of Britain then they would have had an impact on economic growth there too.

Literature Review: Transport and the Emergence of Modern Growth

Britain's domestic transportation network was improved significantly during the eighteenth and early nineteenth centuries in the form of vast improvements to roads and the construction of the canal network. Szostak (1991) and Bogart (2013) have championed the importance of these improvements to the British Industrial Revolution. Szostak distinguishes between the combined knowledge and market access effects of road improvements and the market access effect of canals. Bogart quantifies the effect of roads and canals on passenger journey times and costs and freight rates over the eighteenth century. He finds that stagecoach speeds increased fourfold between 1700 and 1820, from 1.96 to 7.96 miles per hour, with the bulk of the gains occurring after 1750. At the same time, real fare prices rose only slightly from 0.183 shillings per mile to 0.21 shillings per mile in constant 1700 prices. Road freight rates fell from 1.2 shillings per ton mile in 1700 to 0.7 shillings per ton mile in 1800 (in constant 1700 prices), and waterway freight rates fell from 0.43 shillings per ton mile for river navigation in 1730 to 0.12 shillings per ton mile for canal navigation in 1840 (in constant 1700 prices), though the more important contribution of waterway transportation progress was that the canal network greatly extended the geographic coverage of inland waterway navigation, thus dramatically reducing the average cost of freight transportation across the country. Bogart shows that the binding constraints to these transportation improvements were often related to finance and property rights, which in both cases British institutions proved able to overcome. Private order financing in the form of turnpike trusts played a decisive role, and Britain's eighteenth century parliament proved capable of passing an unprecedented flow of land use bills to enable the construction of roads and canals. Transportation during the British Industrial Revolution appears to have been an important channel through which institutional quality and technological capability helped to deliver modern economic growth.

From the second quarter of the nineteenth century, the expansion of Britain's railways augmented the contribution of transportation to British economic output. By 1870, rail passenger travel speeds had reached 23.2 miles per hour, at a cost of 0.08 shillings per mile (in 1700 prices) for second class travel and 0.05 shillings per mile for third class travel, and by 1865, rail freight transportation had reduced freight costs to 0.06 shillings per ton mile. By then, the daily movement of people and goods in Britain – and indeed in the many other countries around the world that were rapidly building national rail networks – proceeded at a pace more akin to a modern than a pre-modern economy.

What do we know in quantitative terms about the economic impact of the rail revolution? The answer is not very much. The most famous contribution to the question is Robert Fogel's finding in 1964 that rail was surprisingly dispensable to the nineteenth century US economy (Fogel 1964). In writing, Fogel was responding to the conventional wisdom at the time, which saw the 'Iron Horse' as the central driving force for nineteenth century American growth (Jenks 1944, Savage 1954, Rostow 1960). Through a pioneering use of the social savings methodology – which measured the marginal contribution of rail to freight transportation costs within the agricultural sector over and above a counterfactual canal-based agricultural freight transportation system that he considered likely to have been constructed in the absence of the railway system – he found that removing all of America's railroads in 1890 and replacing them with a canal system would have reduced US GNP in 1890 by only about 3%.

Fogel's social savings methodology was a highly valuable contribution to both historical and prospective policy studies, but his estimate of the impact of rail on the US economy is likely to be a substantial underestimate. Fogel's analysis did not account for the channels other than agricultural freight costs by which rail is likely to have affected economic growth, such as rail's impact on the growth of cities and therefore on productivity due to scale, agglomeration and specialisation effects, and the effect of rail on technological innovation via knowledge and market access effects. Moreover, many of Fogel's readers mistakenly took his estimate to represent an 'all-in' effect of rail on the economy. As a consequence, rail has been somewhat tainted as a factor in nineteenth century US growth ever since.[73]

Recently, Donaldson and Hornbeck have updated Fogel's analysis using modern GIS techniques to calculate agricultural social savings more accurately, confirming Fogel's estimate. Yet they have retained Fogel's agricultural and static focus. Klein and Crafts (2015) have made progress on the identification of the cities channel, showing that the specialisation of output by cities had a large impact on aggregate labour productivity in US by the turn of the twentieth century. On rail and innovation, Sokoloff, studied the geographical distribution of patenting in the US in the nineteenth century, highlighting disproportionately high patenting

[73] For instance, in the Economic History Review, Lance Davis claimed that Fogel's work shows that "the railroads made some contribution to growth, but…America would not be drastically different if they had never existed." (Davis 1966, pp659). Indeed, one might unsympathetically read Fogel as inviting such an interpretation, given passages such as " " (quoted in David 1975)

rates near canals and other waterways (Sokoloff 1988). Sokoloff explained these higher rates by the lower market access costs that canals and waterways provided to producers, who could transport freight by water cheaper than across land, neglecting the possibility of a knowledge access channel. Transport aside, but relatedly, recently Packalen and Bhattacharya (2015) have examined the relationship between cities and patenting between 1836 and 2010, finding a strong effect, which was stronger still earlier in the period. They attribute this to lower knowledge access costs in cities.

Theory: Romer-Mokyr and the Railways

Specifying the effect of rail on technological innovation via knowledge access costs is a similar task to specifying the effect of KAIs. Both have a spatially differential impact on the cost of access to knowledge, lowering it more in their locality than further away. And in both cases the general equilibrium impact on technological innovation is more complex than the simple aggregate of all the individual local impacts. Like KAIs, the more developed the global rail network the larger the potential gains from the establishment of a local node. In the case of rail, however, there are two further complexities. First, there exists a parallel effect of rail on technological innovation due to rail's impact on market access (Sokoloff 1988). Second, the laying of track in one locale may displace population and economic activity in adjacent locales, potentially raising the cost of access to both knowledge and markets there. However, one is spared the complexities of the effect of KAIs on knowledge access costs, such as the spreading of scientific norms.

With these considerations in mind, I reintroduce the Romer-Mokyr model from chapter 2, adapted for the analysis of rail. Once again, for simplicity assume that each region's propositional knowledge set is a perfect complement to that of the other n regions. Assume also for simplicity that without rail region i can access only its own propositional knowledge set at non-infinite cost. Then the rate of technological innovation in region i is equal to

$$\frac{d\lambda_i}{dt}^{No\ Rail} = L_{R_i}\Omega_i$$

Assuming that *m* of the *n* other regions are connected to the rail network, connecting region *i* changes its rate of technological innovation to

$$\frac{d\lambda_i{}^{Rail}}{dt} = (L_{R_i} + \frac{dL_{R_i}}{dR_i})\left[\Omega_i \cup \bigcup_{j \neq i}^{m \leq n} \Omega_j\right] + \frac{dMA_i}{dR_i}$$

The rate of technological innovation in region *i* is now determined by the union of the propositional knowledge stock of all *m+1* connected regions, the new size of the research labour force in region *i* after cross-regional displacement due to rail connection, and by the change in the market access effect on technological innovation due to rail connection. This theoretical relationship is more likely to be identified using within-region as opposed to cross region estimation. Furthermore, the major econometric challenge is to distinguish between the knowledge and market access effects, to which end I employ two different identification strategies in the two analyses below.

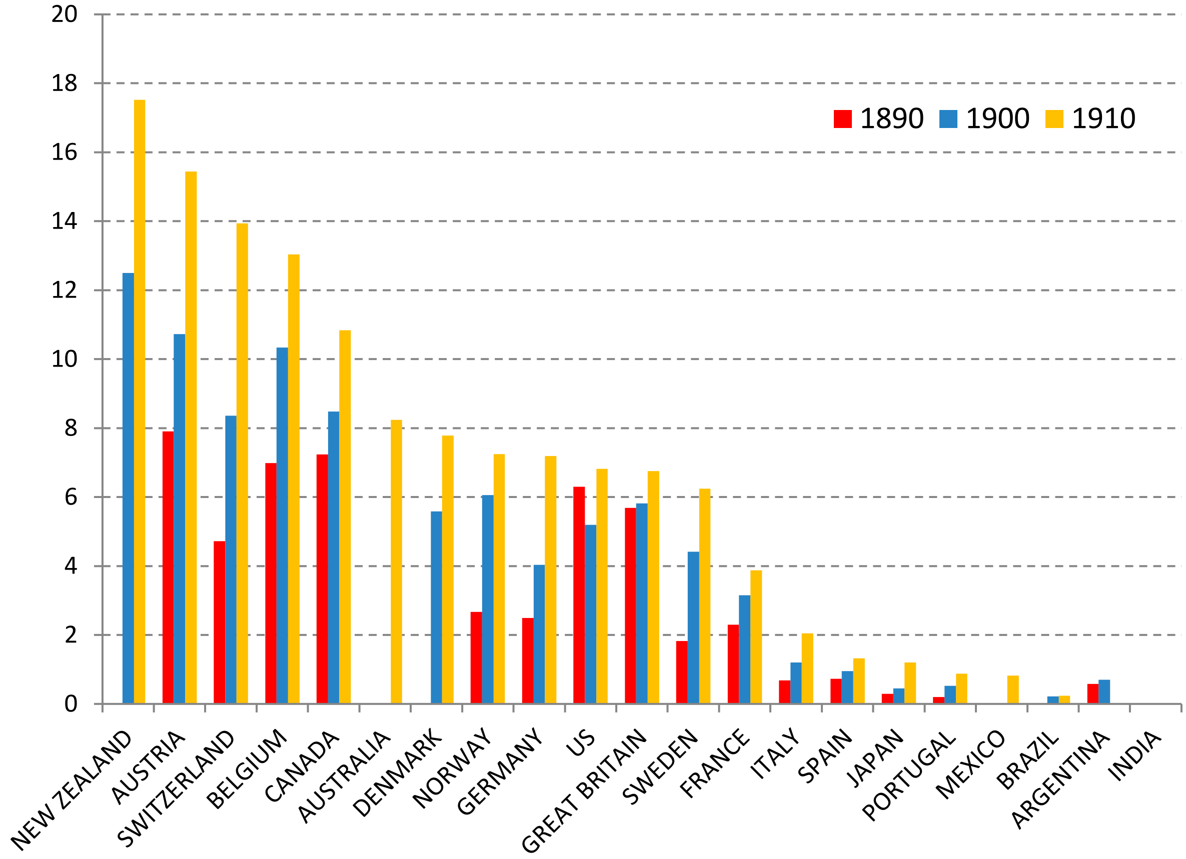
Empirical Analysis A: Passengers, Freight and Patents in 21 Countries, 1883-1913

The first setting in which I investigate the relationship between rail transportation and the rate of technological innovation uses aggregate national annual data on rail and rail activity and national patenting rates as a proxy for the rate of technological innovation across 21 countries between 1883 and 1913.

Data

The rail data comprises rail length (km), annual passenger numbers (m) and annual freight volume (kt) by each country-year. It is taken from Brian Mitchell's statistical compendia (2007a, 2007b, 2007c), which Mitchell collected from national sources. National patent counts are taken from the World Intellectual Property Organization database (WIPO 2014), which provides access to post-1883 counts.

Figure 5.5: Patents per capita, by country, 1890, 1900 and 1910



In addition, annual data on national GDP and population are taken from Broadberry and Klein (2011), where available, and Maddison (2009) otherwise. All countries for which data is available for all variables are included, which are Australia, Austria, Belgium, Brazil, Canada, Denmark, France, Germany, Great Britain, Italy, Japan, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland and the United States. Table 5.2 displays descriptive statistics for this dataset, focused on the years 1890, 1900 and 1910.

Table 5.2: Descriptive Statistics, Means Across Countries by Year

	Year	1890	1900	1910
Patents	*Mean*	6,400	7,442	12,777
	S.D.	2,642	2,522	4,232
Rail Length	*Mean*	30,611	33,069	40,782
	S.D.	16,145	16,358	22,272
Passengers	*Mean*	8,698	16,296	10,028
	S.D.	7,161	11,308	9,686
Freight	*Mean*	3,142	6,036	7,439
	S.D.	1,777	2,967	4,275
GDP per Capita	*Mean*	2,318	2,819	3,515
	S.D.	285	315	379
Population	*Mean*	37,004	35,305	23,226
	S.D.	16,913	15,580	6,518

Estimation and Results

To estimate the relationship between rail length and patenting, I take a within-country OLS estimate of the log of national patents on log rail length using annual data. I control for log population, log GDP per capita and time fixed-effects.[74] Corresponding cross sectional estimates are inappropriate due to the incomparability of patent counts across countries, given large variation in the cost-benefit of patenting between one country and the next owing to variation in market size and legal and procedural variation in patenting systems (Griliches 1990). As column 1 in table 5.3 shows, the within-country estimate of the elasticity of patenting to rail density is 0.76 with a standard error of 0.16. Taken at face value this elasticity is of considerable economic significance given that average rail density across the countries in the sample increased by two and a half-fold between 1883 and 1913. If interpreted causally it would imply that patenting rates increased by around 75% over the period due to railway expansion.

[74] Since a country fixed-effects approach is used it is not necessary to denominate rail length by country area

Table 5.3: Determinants of countries' patents by country-year (and rail passenger and freight elasticities with respect to rail length), 1883-1913

	(1) Patents *Country FE* *Annual* *(1883-1913)*	(2) Patents *Country FE* *Annual* *(1883-1913)*	(3) Rail Passengers *Country FE* *Annual* *(1883-1913)*	(4) Rail Freight *Country FE* *Annual* *(1883-1913)*
Rail Length	0.759***		0.68***	1.38***
	(0.158)		(0.2)	(0.3)
Rail Passengers		0.333***		
		(0.110)		
Rail Freight		0.336***		
		(0.0871)		
GDP per Capita	-0.0817	-0.319	0.68	0.17
	(0.382)	(0.320)	(0.40)	(0.27)
Population	-0.207	0.0551	-0.30	-0.26
	(0.685)	(0.447)	(0.53)	(0.65)
Country FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	518	496	496	496
Countries	21	20	20	20
Years	31	31	31	31
R^2	0.828	0.859	0.852	0.902

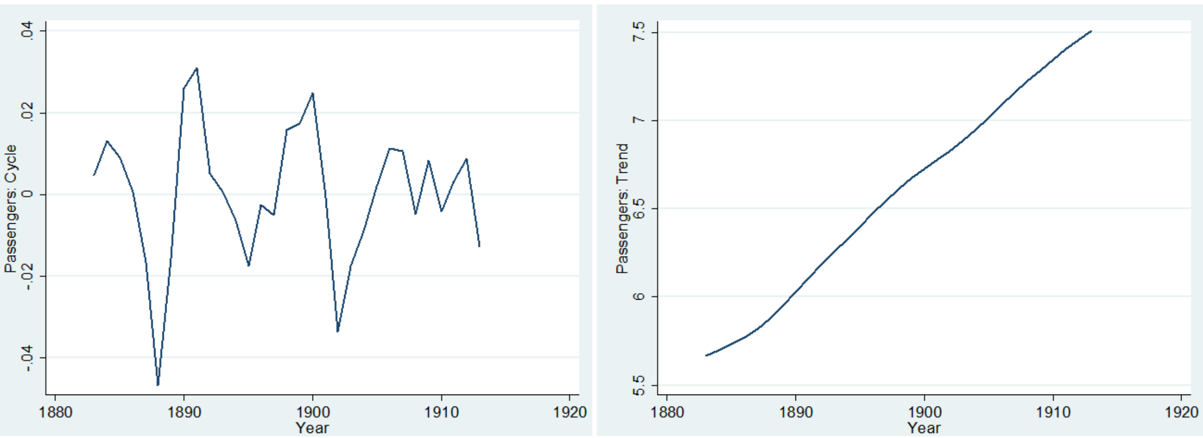
Clustered (by country) robust standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

To attempt to measure the distinct contributions of the knowledge and market access effects of rail, I replace log rail density as a regressor with logged annual passenger volume as a proxy for knowledge access and logged annual freight volume as a proxy for market access. As column 2 in table 5.3 shows, the partial elasticities of passenger numbers and freight volumes turn out to be almost identical to one another, at 0.33. What was the effect of each on patenting? As shown in columns 3 and 4 the within-country elasticities of passenger numbers and freight volume to rail length are 0.68 (with a standard error of 0.2) and 1.38 (with a standard error of 0.3). Multiplying the elasticity of passengers to rail length by the partial elasticity of patents to passengers gives an elasticity of patenting to rail length via the knowledge access channel of 0.22. Calculated similarly, the elasticity of patenting to rail length via market access is 0.45. Adding these two elasticities together gives 0.68, which is close to the overall elasticity of patenting to rail of 0.76 (and well within its standard error), indicating that the overall effect of rail can be accounted for almost entirely through these two channels. The ratio of the two effects is approximately 2 to 1 in favour of market access, indicating that the market access channel was roughly twice as important as the knowledge access channel.

Controlling for the Business Cycle

A problem with these estimates, however, is that they may be biased upwards because annual rail construction, passenger numbers, freight volume and patenting are all likely to vary pro-cyclically with the business cycle, which is largely exogenous to the system of relationships estimated here. Moreover, if within-cycle variation is large relative to between-cycle variation, this bias might be large. The solution is to try to control for the business cycle, either by re-estimating the relationship using variation between data points that are more spaced out over time (i.e. gaps between data points of 5 or 10 years, say) so that within-cycle variation in this specification is smaller relative to between-cycle variation, or by attempting to filter out the cycles in the higher frequency data points and extract the trend. The first of these methods is attractive because it is simple, but it has the downside of omitting many of the data points. The second method allows one to retain most of the data points, but necessarily involves a somewhat arbitrary transformation of the data. Given the shortcomings of each method, I present both.

Figure 5.6: Illustrative HP Decomposition into Cycle (left chart) and Trend (right trend) of Annual Rail Passengers in Germany, 1885-1911



I extract the trends for the rail passengers and rail freight variables using a Hodrick-Prescott (HP) filter (with lambda equal to 6.25, as conventional for annual data), obtaining a cycle and trend component for each. The HP filter requires one to drop the first and last two data points for each country as each filtered data point *t* is calculated as a function of data at *t-2, t-1, t, t+1* and *t+2*. Figure 5.6 shows the resulting HP decomposition for German rail passengers between 1885 and 1911, where the left-hand chart is the cycle and the right-hand chart is the trend. One can see that in the case of Germany the upward trend is quite large relative to the cyclical variation. The spread of the maximum to minimum log value is about 1.75 for the trend compared to about 0.8 for the cyclical component.

Three regressions controlling for the business cycle using the different approaches described above are reported in table 5.4. Columns 1 and 2 show that taking 5 and 10-year intervals to reduce cyclical variation dramatically changes the estimated relative and absolute impact of passengers and freight. In both specifications the elasticity of patents to passengers has doubled to just less than 0.7 and the elasticity to freight has all but disappeared. Using the HP filter, the trend elasticity of patenting to passengers is about 0.3, while the trend elasticity of patenting to freight is insignificant. These results suggest that the relationship between freight volumes and patenting appears to be driven by their co-cyclicality, while the relationship between passenger volumes and patenting appears to be based on co-trends. This evidence does not firmly establish a causal link between knowledge access and patenting rates, but does establishes a strong correlation between the two that is not driven by the business cycle.

Table 5.4: Determinants of countries' patents by country-year, 1885-1910 (controlling for the business cycle)

	(1) Patents *Country FE* *5 yearly* *(1885-1910)*	(2) Patents *Country FE* *10 yearly* *(1890-1910)*	(3) Patents *Country FE* *HP decomposition* *(1885-1911, ann.)*
Rail Passengers	0.690***	0.683*	
	(0.220)	(0.335)	
Rail Freight	0.0293	-0.0809	
	(0.135)	(0.159)	
Rail Passengers: Trend			0.301**
			(0.122)
Rail Passengers: Cycle			0.0173
			(0.0289)
Rail Freight: Trend			-0.0325
			(0.0262)
Rail Freight: Cycle			-0.00569
			(0.106)
GDP per Capita	-0.648*	-0.741	-0.217
	(0.332)	(0.761)	(0.384)
Population	0.634	0.296	0.506
	(0.626)	(0.700)	(0.676)
Country FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Observations	97	51	468
Countries	20	19	21
Years	6	3	27
R^2	0.883	0.891	0.809

Clustered (by country) robust standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Empirical Analysis B: Rail and Patent Quality in US States, 1840-1890

The availability of state-level US data on rail and patents during the era of rapid US railway expansion, along with data on forward citations for these patents presents an alternative strategy to distinguish between the knowledge and market access effects of rail on modern economic growth. The basic idea is that while patent quantity should be affected by both knowledge and market access costs, patent *quality* should be affected only by knowledge access costs. Hence, the identification of an impact of rail on an unbiased indicator of patent quality should be interpreted as evidence of the knowledge access effect of rail on innovation.

Why should the quality of innovation be affected by knowledge access but not market access? The reason is that market access affects the rate of innovation through its impact on *research effort*, while knowledge access affects the rate of innovation through both its impact on research effort and research productivity. In turn, while both research effort and productivity should be reflected in patent quantity, only research productivity should be reflected in patent quality.

Market access and innovation: quantity, not quality

Access to a larger market raises the expected private return to innovative effort and therefore the general equilibrium supply of innovative effort. This effect is discussed in chapter 6 in the context of Robert Allen's induced innovation hypothesis for the Industrial Revolution, and is modelled formally in Acemoglu (2002) and Acemoglu & Linn (2004). Empirically, Acemoglu and Linn provide evidence of a link between market size and research effort in the pharmaceuticals industry, where demographic trends are used as a source of exogenous variation in market size. Furthermore, many empirical studies have shown a link between firm size and R&D expenditure. As larger firms have more sales over which to spread R&D costs, these results can be interpreted as support for a positive effect of market access on research effort (see Cohen 2010 for a survey).

However, research effort has been found not to affect the quality of innovation. For example, Lanjouw and Schankerman (2004) construct a panel of manufacturing firms between 1980 and 1993 and compare R&D expenditure (research effort) with firm patent counts both in cross-section and within-firm. They find a strong correlation of around 0.7[75]. Using a quality indicator of patents they construct based on forward citation counts, they find that the correlation of R&D expenditure with the new quality-adjusted patent count is no higher than with the raw patent count. Lanjouw and Schankerman model patent quality as a stochastic function of R&D effort and conclude that the stochastic component, or luck, dominates the quantity of effort. Tom Nicholas (2014) shows, using a broad dataset of 11,514 US R&D firms between 1921 and 1970, covering many industries, that firm R&D expenditure is positively associated with patent quantity, with an elasticity of around 0.5, which is not too different from Lanjouw and Schankerman's result. However, the elasticity of a firm's total number of patent citations to R&D expenditure is essentially the same as this, once again indicating no effect of research effort on patent quality. Furthermore, in a separate study based on late nineteenth century US patents, Nicholas finds that small independent inventors achieved a slightly higher average level of patent quality than large firms committing larger R&D expenditures (Nicholas 2010).

Knowledge access and innovation: quantity and quality

Lower knowledge access costs raise research productivity, which should be reflected in higher patent citation counts per patent. Ultimately, research productivity is equal to the direct impact of a unit of research labour on labour productivity and capital formation, plus a knowledge-spillover effect – an indirect contribution via any future dependent research (Nelson 1959, Arrow 1962, Griliches 1991). Romer (1990) models research productivity in a framework where the rate of knowledge accumulation is an increasing function of the size of the current knowledge stock. Specifically, research labour is more productive with access to more knowledge. Moreover, Romer and Rivera-Batiz (1991) show within this framework that the integration of knowledge bases across regions, which can be thought of as a reduction in knowledge access costs, also raises research productivity. Research productivity is denominated in Romer's model in terms of aggregate economic output, since research produces new capital goods that raise the productivity of manufacturing labour engaged in producing the

[75] As have many other studies at different units of aggregation, see Griliches 1991 for example. It is significant also that these studies have found that patenting is inelastic with respect to R&D spending. Increasing returns to scale to firms' research effort, while not speaking directly to a quality effect, would suggest a link between research effort and a particular conception of research productivity per unit of effort supplied. As Cohen discusses in an extensive survey of the question, studies have overwhelmingly failed to find these increasing returns to scale (Cohen 2010). In summary, while research effort appears to have an empirically detectable effect on patent quantity, it does not appear to have an empirically detectable effect on patent quality.

economy's single consumer good. Research labour contributes to aggregate output through the direct effect of newly invented capital goods on productivity, plus the indirect effect of the expansion of the knowledge stock on the productivity of research labour in the future. In practice, these effects should be reflected in indicators of patent quality.

In addition, knowledge spillovers also give rise to a research effort effect of drawing some additional labour into the research sector, since the return to labour in the research sector is enhanced relative to its return in the manufacturing sector. As such Romer's model also predicts a positive relationship between knowledge access and the supply of research effort, which should be reflected in patent counts.

Mokyr's (2002) knowledge production function is more nuanced than Romer's because it delineates useful knowledge into two types: propositional (essentially, science and known regularities about the natural world) and prescriptive (essentially, technology). Nevertheless, the positive impact of access to knowledge on the productivity of innovative effort remains central to economic growth. The larger the base of propositional knowledge, and/or the lower are access costs, the faster is the rate of accumulation of prescriptive knowledge (or technological innovation) for a given amount of research effort. For Mokyr, access to a wider base of propositional knowledge raises research productivity for two main reasons. First, with a lower cost of access to knowledge, would-be innovators can choose from a larger set of technological problems to solve. So long as they possess some ability to distinguish problems with higher expect returns from those with lower this will result in higher average research productivity. Second, an innovator trying to solve a given problem can choose from a richer set of potential solutions, and with more information to hand is less likely to pursue erroneous solutions. Mokyr's research productivity effects of lower knowledge access costs should be reflected in patent quality indicators, while access to spillover knowledge should also raise research effort and be reflected in patent counts[76].

[76] Aghion and Howitt (1992) model a similar innovation process to Romer but include the destructive effect of one firm's innovation on the product market share of other firms. This (correctly) complicates the consideration and calculation of the overall contribution of research effort to national income by introducing a negative 'market stealing' externality alongside Romer's positive knowledge spillover externality. However, Bloom, Schankerman and Van Reenan (2013) have shown empirically that the knowledge spillover effect empirically dominates the market stealing effect, so focusing on Romer's positive externality framework appears adequate for our purposes.

Empirically, patent quality appears to capture research productivity and is sensitive to knowledge access. Kogan et al. (2015) show that patent quality, as measured by citation counts, is correlated with research productivity, as estimated by the impact of a firm's patent grant on its equity valuation and subsequent profit growth. Although this measure of research productivity does not capture knowledge spillovers external to the firm, it is a reasonable proxy for the private return to research. Akcigit, Kerr and Nicholas (2013) provide evidence of a positive relationship between knowledge access and patent quality. They examine the entire US patent record from 1836 to 2012, focusing on each patent's usage of the existing technological knowledge base as revealed by its backward citations. They classify patents into three groups depending on their relationship to the pre-existing technological knowledge base: 1) the patent creates a novel technology area, 2) the patent belongs to an existing technology area but incorporates knowledge from a different area and 3) the patent uses knowledge only from its own existing technology area. The average quality of patents by group, based on a forward citation count, suggests a positive relationship between knowledge access and patent quality. Novel technology patents are of the highest quality on average receiving the most citations. They make more use of the existing knowledge base, citing more patents and more technology areas than the other groups. Patents citing combinations of existing technology areas are of the second highest average quality by citations received. They also cite quite extensively and broadly, though not so much as novel technology area patents. Patents engaging with only a single technology area only are of the lowest quality by citations received and make the least use of the existing knowledge base. They cite fewer patents and cite within a narrow technological range. As such, there appears to be a basic correlation between the depth and breadth of usage of the existing knowledge base and patent quality.

Frenken et al. (2012) argue theoretically that innovations combining disparate technology paths, which would likely require particularly broad access to the knowledge base, result in faster technological progress. Empirically, De Vaan, Stark and Vedres (2015) have found that novel combinations of knowledge embodied across computer programmers are associated with the quality of innovation in the computer games industry. Fleming and Sorenson (2004) find a positive link between inventors' use of the scientific knowledge base and patent quality, in line with Mokyr's focus on the importance of the propositional knowledge base. They show that patents citing scientific publications are of higher quality as measured by citations received.

These studies find a link between the extent of an inventor's use of the existing knowledge base and the quality of his invention. However, we are interested in identifying the impact of knowledge access rather than usage, which may be endogenous. Hagedoorn et al. (2006) show using a panel of 152 firms in the IT sector between 1975 and 1999 that a firm's centrality in R&D networks is a predictor of patent quality. Sorenson and Singh (2007) show that science-based patents are of higher quality on average because of the beneficial impact of the scientific norm of openness on knowledge access.

Data and Econometric Model

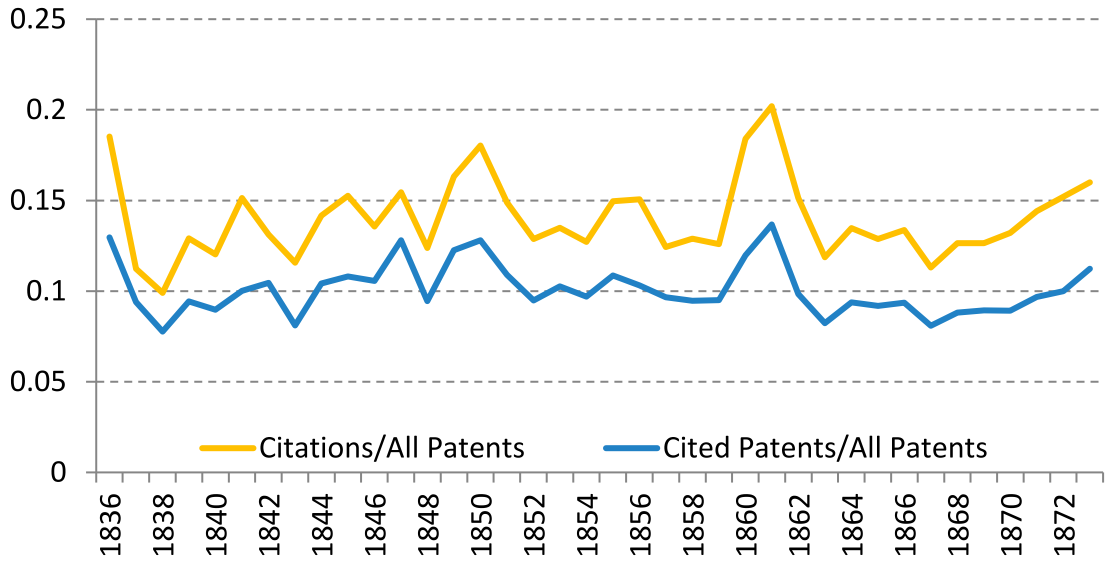
The above discussion suggests that estimating the effect of rail on patent quality should enable one to identify the effect via knowledge access channel. To implement this, I have constructed a panel dataset of US patent counts, forward citation counts, rail density and controls for US states at ten year intervals from 1840 to 1890, although forward citation counts are only available from 1840 to 1870. Rail density is calculated by taking rail length data by state and year from the 1890 edition of *Poor's Manual of Railroads* (Poors 1890). Density is calculated by dividing this length in km by state area as calculated using historical GIS data. Controls for population, urbanisation and economic activity are constructed using decennial census data between 1840 and 1890, accessed at the NHGIS website[77].

To construct patent counts, I use a database of all US utility patents filed between 1790 and 1873, located at the Patent and Trademark Resource Centre Association (PTRCA 2013). The original source for this database is the *Subject Matter Index of Patents for Inventions by the United States Patent Office from 1790 to 1873 Inclusive* (USPTO 1873). I geocode the residence of the first patentee named on each patent by county and state. I categorise each patent by technology class by cross-referencing each patent number with the technology classification database at the US Patent and Trademark Office (USPTO 2013). This database assigns each patent (as identified by patent number) to at least one of around 450 technology classes (e.g. 'plant husbandry' or 'electrical resistors'). Finally, to obtain a forward citation count for each patent, I cross-reference this dataset with the 2001 version of the NBER database of US patent citations, created by Bronwyn Hall, Adam Jaffe and Manuel Trajtenberg (2001),

[77] NHGIS: The 'National Historical Geographic Information System', https://www.nhgis.org/, which provides aggregate census data and GIS-compatible boundary files for the United States between 1790 and 2013.

which lists for each patent granted between 1975 and 1999 the patents it cited. Nineteenth century US patents were cited quite often by US patents granted between 1975 and 1999. Figure 5.7 plots the proportion of patents granted each year between 1836 and 1873 that were subsequently cited between 1975 and 1999; alongside the ratio of 1975-1999 citations to patents for each year. Between 1836 and 1873 consistently around one-tenth of patents received citations during the 1975-1999 period. I create state-level patent counts by year, stratified by industry sector, including forward citation counts for cross-sections 1840 to 1870.

Figure 5.7: Ratio of Cited Patents to All Patents, and Citations/Patents, by Year 1836-1873 (citations from patents during 1970-1995)



Patent citation counts have been used extensively to measure patent quality in studies of innovation. Hall, Jaffe and Trajtenberg (2005) have shown that they are correlated with economic measures of patent value and, as discussed above, Kogan et al. (2015) have shown that they are correlated with research productivity. Nevertheless, one must be careful to ensure that the variation in one’s aggregated citation counts is not biased by omitted variables. Confounding sources of variation in patent counts in the current analysis would stem from any geographical links between patenting frequency in the nineteenth century and citing frequency in the late twentieth century. For instance, consider a cross-sectional regression by state of the count of twentieth century citations of nineteenth century patents on nineteenth century rail density. Although, as argued above, market access should not affect patent quality, states with greater market access should have higher patenting rates via the research effort effect, and simply on a proportional basis exhibit more citations. Given that citations are biased to geographically local patents, due to industry location and knowledge spillover effects (Jaffe, Trajtenberg & Henderson 1993), if industry location and market access patterns across states are persistent between the two periods, the market access of citers in state *i* in the late twentieth century may be correlated with state *i* patent counts in the nineteenth century. As such, nineteenth century market access might be correlated via this indirect route with our measure of patent quality, which would upwardly bias the estimate of the effect of knowledge access. This problem can be overcome, however, by estimating a state-fixed effects model, which utilises within-state variation in rail density and patent citation counts only. As only the market access of the citer, not that of the patentee, is correlated with citation counts, breaking the geographical link between citation variation and rail density variation removes the confounding link.

The long interval between patents and citations means that some technology classifications will no longer be relevant to patents filed during the citation window. This may bias upwards the estimate of the impact of rail density on patent quality, as the local agglomeration effects of rail enabled a more diversified local portfolio of industries, which may have been more likely to contain the exceptional technology areas that retained influence during the late twentieth century. The inclusion of state fixed-effects mitigates this problem. In addition, I normalise each patent's citation count by technology classification and year of filing. The adjusted citation count for each patent is the residual from an OLS regression of logged citation count on year and technology classification for the approximately 150,000 patents filed between 1836 and 1873. The top and bottom citation receiving classifications are shown in tables 6.5 and 5.6.

Table 5.5: Patent Classes Ranked by Mean Citations (1836-1873, citations from patents during 1970-1995): Top 25 Classes

Rank	Class	Mean cites per patent	No of patents 1836-1873	No of Citations	Number Cited	Percent cited
1	Amusement devices: games	2.9	7	20	5	71.4
2	Communications: radio wave antennas	2.0	1	2	1	100.0
3	Earth boring, well treating, and oil field chemistry	2.0	6	12	5	83.3
4	Surgery	2.0	114	228	54	47.4
5	Surgery: splint, brace, or bandage	1.3	89	114	45	50.6
6	Exercise devices	1.1	103	115	52	50.5
7	Optical communications	1.0	1	1	1	100.0
8	Powder metallurgy processes	1.0	2	2	2	100.0
9	Telecommunications	1.0	1	1	1	100.0
10	Synthetic resins or natural rubbers – (subclass 520)	1.0	3	3	3	100.0
11	Surgery	1.0	34	34	20	58.8
12	Aeronautics and astronautics	0.9	104	97	43	41.3
13	Distillation: processes, separatory	0.9	118	107	13	11.0
14	Surgery	0.8	269	217	101	37.5
15	Prosthesis, parts thereof, or aids & accessories	0.8	344	270	101	29.4
16	Package and article carriers	0.8	306	236	116	37.9
17	Surgery: kinesitherapy	0.7	54	36	22	40.7
18	Plant husbandry	0.6	381	230	116	30.4
19	Pipe joints or couplings	0.6	1168	694	380	32.5
20	Amusement devices: games	0.6	194	112	73	37.6
21	Flexible bags	0.5	144	78	43	29.9
22	Wire fabrics and structure	0.5	97	52	16	16.5
23	Fluent material handling	0.5	426	225	110	25.8
24	Needle and pin making	0.5	42	22	4	9.5
25	Chemistry: analytical and immunological testing	0.5	2	1	1	50.0

Table 5.6: Patent Classes Ranked by Mean Citations (1836-1873, citations from patents during 1970-1995): Bottom 25 Classes

Rank	Class	Mean cites per patent	No of patents 1836-1873	No of Citations	Number Cited	Percent cited
352 (joint)	Single-crystal, oriented-crystal, and epitaxy growth processes; non-coating apparatus therefor	0.00	3	0	0	0.0
352 (joint)	Batteries: thermoelectric and photoelectric	0.00	4	0	0	0.0
352 (joint)	Merchandising	0.00	3	0	0	0.0
352 (joint)	Check-actuated control mechanisms	0.00	11	0	0	0.0
352 (joint)	High-voltage switches with arc preventing or extinguishing devices	0.00	1	0	0	0.0
352 (joint)	Selective cutting (e.g., punching)	0.00	14	0	0	0.0
352 (joint)	Radiant energy	0.00	1	0	0	0.0
352 (joint)	Active solid-state devices (e.g., transistors, solid-state diodes)	0.00	17	0	0	0.0
352 (joint)	Electric lamp and discharge devices: consumable electrodes	0.00	6	0	0	0.0
352 (joint)	Electricity: battery or capacitor charging or discharging	0.00	7	0	0	0.0
352 (joint)	Electricity: power supply or regulation systems	0.00	3	0	0	0.0
352 (joint)	Amplifiers	0.00	6	0	0	0.0
352 (joint)	Oscillators	0.00	1	0	0	0.0
352 (joint)	Electricity: electrothermally or thermally actuated switches	0.00	12	0	0	0.0
352 (joint)	Electrical resistors	0.00	19	0	0	0.0
352 (joint)	Coded data generation or conversion	0.00	14	0	0	0.0
352 (joint)	Communications: directive radio wave systems and devices (e.g., radar, radio navigation)	0.00	1	0	0	0.0
352 (joint)	Incremental printing of symbolic information	0.00	3	0	0	0.0
352 (joint)	Television	0.00	2	0	0	0.0
352 (joint)	Electric power conversion systems	0.00	2	0	0	0.0
352 (joint)	Dynamic information storage or retrieval	0.00	1	0	0	0.0
352 (joint)	Industrial electric heating furnaces	0.00	3	0	0	0.0
352 (joint)	Pulse or digital communications	0.00	1	0	0	0.0
352 (joint)	Electrical pulse counters, pulse dividers, or shift registers: circuits and systems	0.00	6	0	0	0.0
352 (joint)	X-ray or gamma ray systems or devices	0.00	1	0	0	0.0

I estimate the following equation on US states at ten yearly intervals between 1840 to 1870, using OLS:

$Ln(PATENT\ CITATIONS\ RECEIVED + 1)_{it} = \alpha + \beta_1 LnRAIL\ DENSITY_{it} + \beta_2 LnPATENTS_{it} + \beta_3 LnPOPULATION_{it} + \beta_4\ \%\ OF\ POP\ IN\ CITIES_{it} + \beta_5\ \%\ OF\ POP\ IN\ TOWNS_{it} + \beta_6 LnMANU.\ \&\ AGRI.\ OUTPUT_{it} + + \beta_7 RATIO\ OF\ MANU.\ TO\ AGRI.\ OUTPUT_{it} + \delta_j + \gamma_t + \varepsilon_{it}$ (5.1)

and in alternative specifications replace patent citations in state-year *it* with i)adjusted-patent citations in state-year *it* and ii)cited-patents in state-year *it* only (i.e. only patents that received at least one citation are counted) as barriers to citation – particularly given such a long lag – are likely to be larger for the first than for subsequent citations. Population, urbanisation and economic activity variables are included as they are likely to be correlated both with rail density and patent quality via knowledge access links. I include full sets of both state and time-fixed effects.

Results

As a first step, I estimate the basic relationship between the log patent count and log rail density in state-year *it* both in the cross section (using the six cross sections between 1840 and 1890 and time fixed-effects) and within-state over time, controlling for state population, the proportion of state population in cities and towns, current dollar output of the agricultural and manufacturing sectors and an indicator of industrialisation (manufacturing/agricultural output). As table 5.7 shows, the elasticity of state patenting with respect to rail density is 0.25 in the cross section and 0.39 within-state. The within-state elasticity is half the average national within-county elasticity between 1883 and 1913 of around 0.8, found above.

Estimation results for equation 5.1 are displayed in table 5.8. Column 1 shows that, controlling for the underlying patent count, the elasticity of raw citations to rail density is 0.3 and highly statistically significant with a standard error of 0.08. As column 2 shows, when controlling only for cited patents this elasticity falls to 0.064, but remains statistically significant with a standard error of 0.028. As columns 3 and 4 show, the elasticity of adjusted citations to rail density is 0.49 controlling for all patents and 0.26 controlling for cited patents only.

Table 5.7: US Patents and Rail Density by State-Year, 1840-1890

	(1)	(2)
	Patents *State Cross Sections 1840-90, 10 yearly*	Patents *State FE 1840-90, 10 yearly*
Rail Density	0.249***	0.385***
	(0.0654)	(0.0672)
Population	0.231	0.842***
	(0.194)	(0.201)
% of Population in Cities	0.137	0.0520
	(0.0925)	(0.0499)
% of Population in Towns	0.209*	-0.193**
	(0.109)	(0.0878)
Agri. & Manufact. Output	0.576***	0.0342
	(0.154)	(0.160)
Manuf. to Agri. Output Ratio	0.125	-0.173
	(0.127)	(0.142)
State Fixed Effects	No	Yes
Time Fixed Effects	Yes	Yes
Observations	230	230
States	48	48
Years	6	6
R^2	0.934	0.965

Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5.8: US Patent Citations (by US Patents filed 1970-1995) and Rail Density, by State-Year, 1840-1870

	(1) Citations during 1970-95 *State FE* *1840-90,* *10 yearly*	(2) Citations during 1970-95 *State FE* *1840-90,* *10 yearly*	(3) Adjusted Citations during 1970-95 *State FE* *1840-90,* *10 yearly*	(4) Adjusted Citations during 1970-95 *State FE* *1840-90,* *10 yearly*
Rail Density	0.291***	0.0640**	0.485***	0.260**
	(0.0766)	(0.0280)	(0.152)	(0.114)
Patents	0.464***		0.793***	
	(0.138)		(0.208)	
Cited Patents		1.110***		1.452***
		(0.0401)		(0.173)
Population	-1.694***	-0.0346	-1.256**	1.020**
	(0.264)	(0.133)	(0.620)	(0.480)
% of Population in Cities	0.225***	-0.00528	0.204	-0.0608
	(0.0829)	(0.0290)	(0.156)	(0.140)
% of Population in Towns	0.142*	0.0170	0.0393	-0.144
	(0.0807)	(0.0401)	(0.195)	(0.236)
Agri. & Manufact. Output	0.913***	-0.00259	0.452	-0.711**
	(0.211)	(0.100)	(0.419)	(0.324)
Manuf. to Agri. Ouput Ratio	0.0153	-0.0363	0.158	0.0361
	(0.108)	(0.0347)	(0.167)	(0.137)
State Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Observations	139	139	139	139
States	48	48	48	48
Years	6	6	6	6
R^2	0.883	0.985	0.851	0.920

Robust standard errors, clustered by state, in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; Adjusted Citations are citations adjusted for the average citations received in each sectoral classification.

Conclusion

There exists a basic correlation between KAIs and the emergence of modern economic growth across countries during the late nineteenth and early twentieth centuries. Does this link have a causal dimension?

Two analyses in this chapter have established a positive relationship between rail and patenting during the age of the rail transportation revolution. What role did falling knowledge access costs, as opposed to falling market access costs, play in this relationship? The identification strategies used above suggest that knowledge access played a distinct role. First, controlling for the influence of the business cycle, the rise in rail passengers appears to have been more important than the rise of rail freight in determining national patenting rates in the late nineteenth and early twentieth centuries. Second, rail had a significant effect on the quality of patenting in the nineteenth century US, which, as argued above, is likely to represent the footprint of the knowledge access effect of rail. This evidence suggests that knowledge access costs were a binding constraint to the emergence of modern economic growth in an international context during the late nineteenth and early twentieth century. KAIs may have operated upon this constraint.

In addition, this chapter challenges Robert Fogel's result of rail's modest impact on nineteenth century US economic growth (Fogel 1962). Fogel showed that railways made the economy of the day a bit more efficient. However, they also helped to create the economy of tomorrow.

Chapter 6

The Demand for Technology and the Emergence of Modern Economic Growth

Robert Allen has argued that eighteenth century British inventors and entrepreneurs were not particularly capable innovators, but instead were uniquely well incentivised to innovate. In this spirit, he has documented Britain's relatively high wages and low energy prices and shown how they made some of the great labour-saving macroinventions of the British Industrial Revolution more profitable to adopt, and so invent, in Britain than elsewhere (Allen 2009). But how much of a contribution did this incentive to innovate make to the *overall* acceleration in technological progress that characterised the British Industrial Revolution? Was it, as Allen claims, the main driving force?

Moreover, is the incentive presented by high wages and cheap capital and energy to substitute labour for machines the main mechanism underlying modern economic growth *in general*, as Allen also claims (Allen 2012)? Or rather, were expensive labour and cheap capital and energy perhaps more akin to the starter motor of modern economic growth, sparking a cluster of seminal innovations in eighteenth century Britain, but not themselves the engine? Was that engine instead an improvement over time in the capabilities required for innovation?

This chapter aims to shed some light on these questions by attempting to measure the contribution of Allen's incentives to aggregate productivity growth in the manufacturing sector during the early stages of modern economic growth, using data for the United States in the late nineteenth century. Clearly, the British Industrial Revolution and the subsequent emergence of modern economic growth in the United States were distinct events, so such an analysis cannot speak directly to the question central to this thesis of the cause of the British Industrial Revolution. Nevertheless, the high wages and low energy costs that Allen claims incentivised the British Industrial Revolution also prevailed in the late nineteenth century US economy owing to America's abundant land and natural resources and relatively scarce labour (Habakkuk 1962, Allen 2014). Indeed, due to this similarity between the two cases, Allen sees the British Industrial Revolution as the 'prequel' to America's late nineteenth century transition to modern economic growth (Allen 2009). In the context of this thesis, the American case is interesting because of the availability of rich, sub-national data on output, factor inputs and wages for the US manufacturing sector in the late nineteenth century (owing to the decennial US *Census of Manufactures*), which enables one to examine the effect of Allen's incentives in a more comprehensive way than one can for the British Industrial Revolution, but while retaining the context of an early experience of the transition to modern economic growth (Abramovitz & David 2001). If, by examining this evidence, Allen's incentives can be shown to have influenced the American transition to modern economic growth then this would lend plausibility to the claim that they influenced the British transition too.

Second, Allen has shown using national-level panel data for the period from the British Industrial Revolution until the late twentieth century that countries with higher capital-labour ratios have tended to experience faster subsequent rates of labour productivity growth due to a faster subsequent rate of both technological progress and capital accumulation. Conversely, countries with relatively low capital-labour ratios have experienced little labour productivity growth. He interprets this finding as evidence of a positive feedback loop generated by labour-saving innovation, whereby rising capital intensity raises wages and incentivises further labour saving innovation, and provides increasing scope for learning by doing. He argues that this is the underlying engine of modern economic growth and the reason for the Great Divergence between rich and poor countries during the past two centuries (Allen 2012). The more coherently any explanation for the British Industrial Revolution fits with our understanding of the broader experience of modern economic growth the more plausible it is. As such, if correct, Allen's explanation of modern economic growth as the self-sustaining process of labour-saving innovation lends plausibility to his view of the British Industrial Revolution as the grinding into motion of the wheels of this process.

However, Allen's interpretation of the positive relationship between national capital-labour ratios and subsequent national productivity growth rates during the past two centuries is subject to a major omitted variable problem. The historical economic development of today's rich countries may have been conditional on capabilities that they attained at some point in the past, but which have eluded poor countries. If these capabilities are difficult to attain but persistent once attainted[78] then one ought to expect divergent levels of technology, capital stocks and productivity between high and low capability countries irrespective of the existence

[78] For example, Rocha, Ferraz, & Soares (2015) provide evidence on the long run persistence of human capital.

of a positive feedback mechanism within the mechanics of capital accumulation and technological change itself. The capabilities thought to be important for modern economic growth – such as appropriate institutions (Acemoglu & Robinson 2012), an adequate educational system (Hanushek & Woessmann 2015) or an innovative culture (Mokyr 2016) – are likely to vary less within a single country than between countries. As such, investigating these relationships in American counties rather than national economies may help one to distinguish between the two interpretations.

I specify four logical implications of Allen's argument, which suggest four empirical tests of its validity and an approach to measuring its quantitative importance to the emergence of modern economic growth in the late nineteenth century American context:

1. *Can we detect an overall labour saving bias in nineteenth century US technological change?*

2. *Did capital-labour ratios rise faster where labour was more expensive relative to capital?*

3. *Was productivity growth faster where capital-labour ratios were higher?*

4. *Was more innovative effort expended where the returns to innovation were higher?*

Taken together, the answers found to these four questions lend support to Allen's argument for the importance of demand-side incentives to the acceleration in modern economic growth in the US case. Nevertheless, Allen's incentives are found to fall short of plausibly accounting for all of this acceleration. This leaves room for the contribution of an improvement in supply-side capabilities.

Allen's Hypothesis

To carefully specify Allen's hypothesis, I closely follow Crafts' discussion of Allen's 2009 book, *The British Industrial Revolution in Comparative Perspective* (Crafts 2011). Allen states that his theoretical framework is based on Paul David's attempt in 1975 to pin down the theory underlying H.J. Habakkuk's argument for late nineteenth century American technological superiority (David 1975, Habakkuk 1962). Habakkuk, David and Allen write in the tradition of the literature on factor substitution and induced technological change that began with John Hicks' insight that: "The real reason for the predominance of labour-saving inventions is surely that…a change in the relative prices of the factors of production is itself a spur to innovation and to inventions of a particular kind – directed at economizing the use of a factor which has become relatively expensive" (Hicks 1932, pp.124-5).

Mokyr (2009) and Jacob (2014) object to Hicks' statement pointing out that a producer would be equally interested in cost savings made by economizing on any factor of production, regardless of its price. As such, factor prices do not directly determine the bias of technological change. Mokyr also points out that Christine MacLeod's survey of a sample of patent records during the British Industrial Revolution fails to identify saving labour as a significant objective of inventors (MacLeod 1988). However, David and Allen's arguments are sophisticated enough to survive these objections. As shown below, although relative factor prices may not necessarily bias technological change directly, they can do so through a multi-step, path dependent process. Second, patentees may have been reluctant to document their intention to save labour during the British Industrial Revolution because of public backlashes against industrialists replacing labour with machines.

David and Allen's arguments can be illustrated by figures 6.1 and 6.2, which show the two steps by which expensive labour relative to the cost of capital may lead to sustained technological progress. Given the curved isoquant in figure 6.1, if an economy faced the isocost line, P_0, which is associated with relatively cheap labour and expensive capital, it would choose technology A (where its isocost line is tangential to the isoquant curve). Similarly, an economy facing the isocost line P_1 (where labour is relatively expensive and capital relatively cheap compared to first economy) would choose the more capital intensive technology, B. Now, if the idea for a new macroinvention suddenly made point C possible, only producers in the high wage economy could be incentivised to switch because given factor price ratios P_1 and P_0, point C dominates B but not A. Whether the economy operating at B switches to C or not depends on the fixed cost and expected revenue stream of the associated R&D investment, the latter determined largely by the addressable market size.

Figure 6.1: Step 1. Factor Prices and Macroinvention

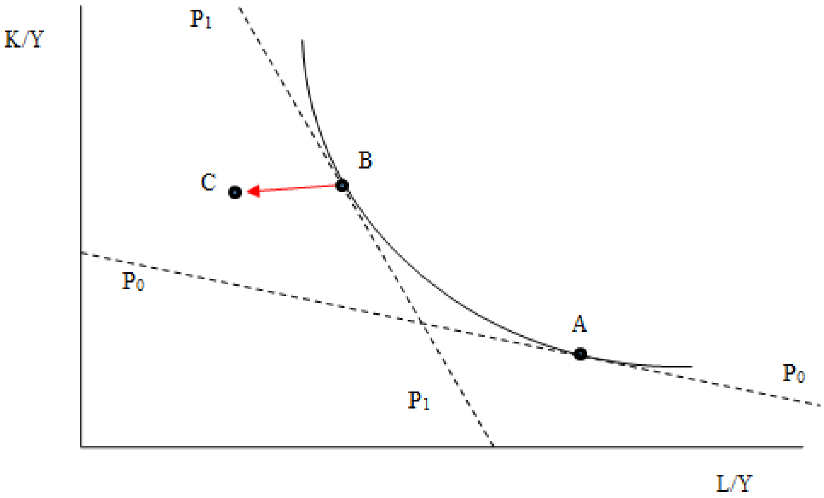
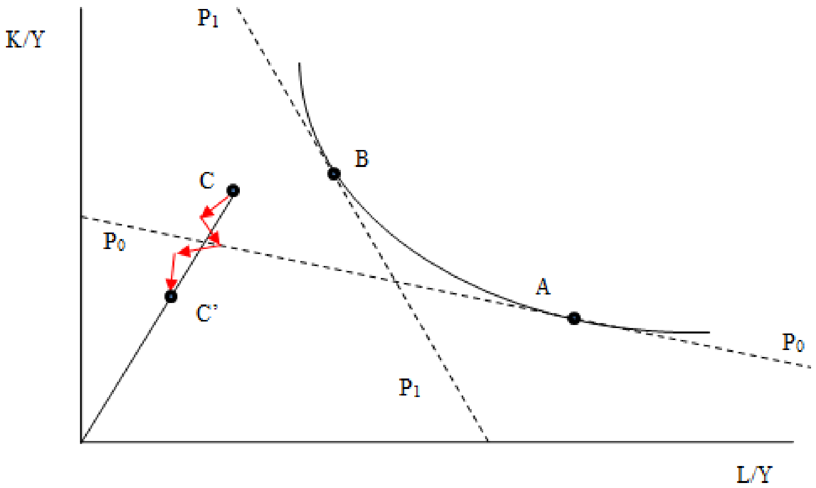


Figure 6.2: Step 2. 'Local Learning' with Capital Intensive Technology



Note two implications of this for the debate between supply and demand side explanations of the British Industrial Revolution. First, market size matters to the incentivisation of the macroinvention and may, in principle, be more important than relative factor prices.[79] Allen cites Britain's market size in the eighteenth century as an advantage over Holland. Nevertheless, it does not feature in his main narrative nor empirical work. Nor has it been discussed much in the subsequent debate on Allen's book, Crafts' review aside[80]. Second, the viability of the macroinvention is also dependent on the productivity of R&D, since this helps to determine R&D costs. Given that the capabilities explored in this thesis operate largely

[79] Induced innovation depends on these two factors in Acemoglu (2002)
[80] Crafts & O'Rourke (2013) discuss it

through their effect on the productivity of R&D effort, Allen's account of the Industrial Revolution is clearly compatible with an account based on such capabilities.

If adoption is profitable (taking into account R&D costs and market size) then the macroinvention is adopted and the higher wage economy moves from point B to C and its capital-labour ratio rises. As the gap between capital-labour ratios in the two economies has widened, so has the relative potential for *learning by doing* – the generation of incremental productivity gains due to cumulative experience using the new technology (Arrow 1962). Allen, following David (1975 pp 68-91), argues that the subsequent burst of learning in the high wage economy should be neutral in its factor saving properties, or at least so *ex ante*. Technological progress then, in the form of a factor-neutral flow of microinventions, would proceed at point C, taking the high wage economy to, say, C' (figure 6.2). At the same time, aggregate learning would be relatively stagnant in the low wage economy (still at point A) and may remain so until the high wage economy improves the new technology through learning effects to the extent where the P_0 isocost line is crossed. In Allen's words, "nothing much happens in the low wage country."

Once the high wage economy crosses P_0, however, the new technology becomes profitable to adopt in the low wage economy too (conditional on its market size and locally required R&D expenditure). This is an important feature of Allen's story. First, it enables one to explain the spread of modern economic growth as a function of the global technological frontier and local adoption costs. Second, it enables one to explain why Britain's economic growth performance declined in the decades following the British Industrial Revolution. Britain lost international market share once it improved the efficiency of its technology to the point that it became profitable to adopt in other countries. Britain was a victim of her own success.

Although this mechanism produces the bulk of productivity gains via the learning step, it can only deliver long run economic growth if new macroinventions are forthcoming owing to the diminishing returns accruing to the existing capital stock. This necessity is described formally by Alwyn Young in a 'hybrid' endogenous growth model that contains both R&D and learning by doing (Young 1993). Indeed, David emphasises the importance of scientific institutions to R&D and the supply of breakthrough innovations (David 1975). However, although Allen acknowledges that the Scientific Revolution may have been a pre-condition for the Industrial Revolution, he plays down its importance. Rather, he invokes a feedback mechanism to explain sustained long-run growth, where rising capital-labour ratios cause labour productivity and wages to rise, which incentivises further labour-saving macroinventions.

Although Allen does not do so, it is important to distinguish between high wages and high labour costs *per se*, particularly since Allen's evidence of comparatively high eighteenth century British wages is based on time rates not piece rates. Technological innovation raises labour productivity and, so long as labour's bargaining power is not too weak, tends to raise wages. But if labour productivity growth is large relative to wage growth, it will not necessarily raise unit labour costs. If British unit labour costs fell relative to those of its competitors once the British Industrial Revolution proceeded, then rising wages would not have incentivised further labour saving innovation. Allen's positive feedback mechanism between rising wages and capital accumulation can be revived by invoking a general equilibrium effect of wages in the technologically progressive sector of the economy on wages in the rest of the economy. The basic mechanism for this, as explained by William Baumol (2012), is that competition for labour between the progressive and stagnant sectors means that productivity and wage growth in the progressive sector can cause wages to be bid up in the stagnant sector too. Note, however, that the strength of this general equilibrium effect would be dependent on the proportion of the labour force employed in the progressive sector, which was small in the early stages of the British Industrial Revolution (Crafts 1985).

Empirical Questions

The above theoretical framework highlights at least four testable and measurable implications of Allen's hypothesis for the observed relationships between factor prices, factor ratios and productivity growth, and profitability and innovation, during the emergence of modern economic growth:

Implication 1: An overall capital bias to technological change

The movement of the high wage economy from B to C' implies that technological change imparts an overall labour-saving bias to the isoquant curve, which now passes through C' rather than B. Nevertheless, one would not expect the patent records of the high wage country to reveal an overall bias towards the aim of saving labour, even after controlling for patentee reticence in the face of public backlashes against labour saving machines. This is because they would be dominated by the neutral microinventions of step 2. In contrast, although macroinventions radically change factor proportions, they are, by nature, rare. Hence, MacLeod's finding that patentees did not state that they were trying to save labour does not (and cannot) contradict Allen's argument.

Crafts points out that the overall labour saving bias would be observable, however, as a fall in the wage share of value added as the capital-labour ratio rose over time. To attribute an observed correlation between a rising capital-labour ratio and a falling wage share to labour-saving bias one must assume that the elasticity of substitution between capital and labour, which cannot be directly observed, is not too high. If the elasticity of substitution between capital and labour is less than one,[81] as most empirical studies suggest (see Leon-Ledesma et al. 2010 for a survey), then a negative correlation between the capital-labour ratio and the wage share of value added can be taken as evidence of a labour-saving bias to technological change.[82]

Using this approach, Allen provides evidence of a labour-saving bias during the British Industrial Revolution (Allen 2009b), however, he assumes an elasticity of substitution between capital and labour of 0.2, which could be considered quite low. Moreover, the falling wage share during the British Industrial Revolution may have reflected an adverse shift in the bargaining power of labour relative to the owners of capital, rather than technological bias (Stiglitz 2015, Jaumotte & Osorio Buitron 2015). One way to strengthen the hand of the technological bias interpretation would be to test for a correlation using sub-national panel data. Although the bargaining power of capital relative to labour could in principle be positively correlated with capital-labour ratios across regions, this would clearly put greater demands on the bargaining power argument since labour mobility across regions would have acted to dampen regional differences in labour's bargaining power. As such, cross-sectional correlations and within-region correlations over time would provide somewhat stronger

[81] I.e. that the marginal productivity of capital relative to that of labour falls when the capital labour ratio rises, given constant technology or unbiased technological change

[82] Although it is essential to note that the absence of a negative correlation would not provide the same degree of support to the alternative hypothesis of the absence of labour saving bias, since it may just be the case that the effect of the labour saving bias on the wage share is more than offset by diminishing returns to capital per worker as the capital labour ratio rises

evidence of the labour-saving bias to technological change than the correlation in the aggregate time series.

Implication 2: Manufacturing firms accumulated capital faster when they faced higher unit labour costs

Allen argues that new waves of technological change in the eighteenth and nineteenth century were set in motion by labour saving macroinventions, whose rates of adoption across different locations were determined by the local cost of labour relative to capital and energy costs. This is the intuition behind the shift of the high wage/cheap capital economy from point B to C while the cheap labour/expensive capital economy remains at A. If this mechanism is important at the aggregate level, as Allen claims, then one would expect to see faster rates of capital accumulation in regions where labour was expensive relative to capital and energy costs.

Implication 3: Total factor productivity growth was higher at higher capital-labour ratios

Allen's argument also implies that total factor productivity growth should be higher where capital-labour ratios are higher, owing to higher rates of learning by doing, i.e. progress is made from point C to C' while there is relative stagnation at point A. This mechanism helps to explain why modern economic growth, if driven by labour saving induced innovation, is self-sustaining. It also helps to explain the Great Divergence of rich and poor countries during the past two centuries.

Implication 4: More innovative effort was expended when private returns to innovation were higher

Allen argues that if a technological innovation is more profitable to adopt in a certain economy then it is also more likely that it will also be invented there, given the costly research and development required. For example, the superior profitability of the Spinning Jenny in Britain made it more likely that it was invented in Britain rather than elsewhere. Hence, innovative effort in region *i* should be correlated with the potential returns to innovators in region *i*. This will be determined by the number of potential adopters addressable by region *i*'s innovators, which is a function of the market access of region *i*'s innovators and relative factor prices weighted by distance from region *i*.

Data and Empirical Specifications: Manufacturing in American Counties in the Late Nineteenth Century

The US economy experienced the onset of modern economic growth during the nineteenth century. As in the earlier British case, it was a gradual process. According to Abramowitz and David (2001), US labour productivity in the private domestic economy grew by about 0.4% per annum in the first half of the nineteenth century, which was already quite a high rate by historical and contemporary standards. Between 1855 and 1871, owing at least in part to economic disruption associated with the Civil War, labour productivity growth fell to an average rate of only about 0.1% per annum. However, from 1871 onwards labour productivity increased at a rapid clip, rising by about 1.5% per annum between 1871 and 1905. This acceleration in labour productivity growth was in turn largely due to an acceleration in total factor productivity (TFP) growth, the hallmark of modern economic growth. Between 1800 and 1855 TFP growth contributed 0.2% of the 0.4% annual growth in labour productivity, but between 1871 and 1905 it contributed around 0.9% of the 1.5% annual labour productivity growth.

The manufacturing sector employed only quite a small, although growing, share of the labour force during the period of emerging modern economic growth in the United States: 17.6% in 1869 and 22.1% in 1909. This was significantly lower than in Britain, where 33.5% of the labour force were employed in manufacturing in 1871 and 32.1% in 1911 (Broadberry & Irvine 2005). Furthermore, many of the sources of modern economic growth in the US between 1870 and the early twentieth century were to be found outside of the manufacturing sector, such as improvements in transportation and communication (Abramovitz & David 2001). Nevertheless, the growth of labour and total factor productivity in manufacturing in the period following 1870 was typical of the economic progress taking place. According to Kendrick's calculations (Kendrick 1961, p464, table D1), manufacturing labour productivity grew by 1.6% per annum between 1869 and 1899, of which 1.3% per annum was due to an increase in total factor productivity.

The Census Act of 1850 mandated a decennial *Census of Manufactures,* following two ad hoc manufacturing industry supplements to the population census in 1820 and 1840. From 1850 until 1900 the Census of Manufactures was conducted under this mandate, in principle surveying all manufacturing establishments in the United States with a gross annual output greater than $500. It recorded the number of workers employed and wages paid, the value of the capital stock accumulated, the annual value of raw materials used and the annual value of output produced. The results were aggregated at county, state and national levels and published in the official census reports, which can be found at the *United States Census Bureau*[83]. These aggregates have been electronically transcribed by the Minnesota Population Centre at the University of Minnesota, as part of the National Historic Geographic Information System (NHGIS) project, and are available at https://www.nhgis.org/ (NHGIS 2011).

Using this data, I construct a county-decade panel dataset on the late nineteenth century US manufacturing sector to test the four implications of Allen's hypothesis set out above. I focus on the period 1870 to 1900, which captures the early decades of rapid modern economic growth in the US while avoiding the period of disruption and apparent stagnation associated with the Civil War. The manufacturing censuses taken after 1900 lack sufficient continuity with respect to the pre-1900 censuses to be included in the panel, as important variables are discontinued. As such, I construct the panel based on the Censuses of Manufactures for the years 1870, 1880, 1890 and 1900. As explained below, testing some of the implications of Allen's hypothesis in this setting requires the use of dynamic panel data models, which require the construction of instrumental variables based on lagged regressors to mitigate endogeneity problems. To accommodate this, I append to the panel observations for the 1840, 1850 and 1860 manufacturing censuses with which to construct instruments for the post-1870 data. All manufacturing data is accessed from version 11 of the NHGIS database (NHGIS 2011). For each county and census year I construct variables representing manufacturing capital-labour ratios, manufacturing labour productivity levels (manufacturing value-added per worker, where value-added equals the value of output minus the value of raw materials) and manufacturing unit labour costs (average wage per worker divided by average value-added per worker).

The censuses recorded current dollar values of manufacturing inputs and outputs. To focus on their real changes over time, I construct a set of deflators to convert all observations to constant 1900 dollar amounts. I deflate manufacturing output and wages by Robert Gallman's goods deflator, published in Gallman (1966) and Rhode (2002) and raw materials by Warren and Pearson's all commodities deflator, as published by the US Census Bureau (US

[83] https://www.census.gov/history/www/through_the_decades/overview/

Census Bureau 1975). I deflate the manufacturing capital stock by a weighted average of four deflators representing its four components. For machinery, I use Gallman's producer durables deflator (Rhode 2002); for structures, an average of Warren and Pearson's and Gallman's construction deflators (Rhode 2002); for inventories, an average of Gallman's total goods and Warren and Pearson's all commodities deflators; and for land, county-specific deflators constructed from census data on the price of farmland per acre by county, accessed from version 11 of the NHGIS database (NHGIS 2011). The weights for the four components of the capital deflator are based on the average share of the four capital components in the overall capital stock as measured in the 1890 and 1900 censuses (discussed below). Where annual deflator series are available, I take a three-year average centred on the year of data collection for each census.[84]

It is important to evaluate how appropriate the manufacturing capital stock recorded by the census is for testing Allen's theory. Allen's factor price-induced incentives to accumulate capital per worker in the manufacturing sector are envisaged to operate primarily on the machinery component of the manufacturing capital stock. Likewise, learning by doing is envisaged to take place when using machinery (Delong and Summers 1991)[85]. However, the US manufacturing capital stock is delineated into its four components of machinery, land, buildings and inventories only in the 1890 and 1900 censuses, previous censuses recording only the aggregate. Allen's theory describes dynamic relationships between economic variables, such as the effect of unit labour costs in year *t* on the subsequent rate of growth of capital per worker. As such, if one wishes to represent the capital labour ratio by the machinery capital stock per worker, the availability of only two time-series observations of the machinery capital stock for each county (one for 1890 and one for 1900) allows only a cross sectional analysis of some of the implications of Allen's theory. This is problematic because unobserved economic heterogeneity across counties is likely to confound estimation in the cross-section.

Within-county estimation is a better approach than cross-sectional because it enables one to control for time-invariant heterogeneity across counties. As such, a key question is how closely related variation in manufacturing capital per worker is to variation in manufacturing

[84] The manufacturing data were collected for each census in year t-1 for each census, i.e. 1870 census, data was collected in 1869.

[85] Indeed, Field (1985) has emphasised the importance of distinguishing between machinery and the capital stock more broadly when evaluating Habakkuk's hypothesis by comparing nineteenth century capital-labour ratios in Britain and the US.

machinery per worker. In the 1890 and 1900 censuses the machinery component accounts for only 29% and 32% of the national manufacturing capital stock respectively, while land accounts for 14% and 15% respectively, buildings 16% and 21% and inventories 40% and 32%. However, the correlation between logged machinery per worker and logged capital per worker across counties is high at 0.73 in 1890 and 0.76 in 1900. Moreover, the correlation in the change in log machinery per worker and log capital per worker between 1890 and 1900 across counties is also high, at 0.79. These correlations seem high enough to justify the use of aggregate manufacturing capital per worker to represent Allen's capital-labour ratio. Indeed, Allen uses aggregated capital stocks when illustrating his theory using national level data (Allen 2012).

I also add to the panel county-level data on population, market access and manufacturing patent counts. The population variables are based on the census, taken from version 11 of the NHGIS database, and are added for all census years. County-level market access for 1870 and 1890 is calculated and kindly donated by Dave Donaldson and Richard Hornbeck (Donaldson & Hornbeck 2016). The manufacturing patent count by county is available for 1870 only and is based on the US patent spatial database constructed for this thesis, introduced in chapter 3. Descriptive statistics for all variables are displayed in table 6.1.

The existence of an overall capital bias in technological change (Implication 1) is the only one of the four implications above that can be tested within-county using the machinery component of the capital stock. This is because the relationship in focus is between two static variables – the manufacturing capital-labour ratio at time *t* and the wage share of manufacturing value-added at time *t* – and so requires only two cross sections to obtain an average within-county estimate. I estimate the within-county effect of the manufacturing machinery stock to worker ratio on the wage share of manufacturing value-added per worker between 1890 and 1900. I also estimate the effect of the overall capital stock per worker, based on the full panel. I estimate the following two equations using OLS:

$$WAGE\ SHARE\ OF\ MANUFACTURING\ VALUE\ ADDED_{it} = \alpha + \beta_1 LnMACHINERY\ PER\ MANUFACTURING\ WORKER_{it} + \delta_j + \gamma_t + \varepsilon_{it}$$

$$WAGE\ SHARE\ OF\ MANUFACTURING\ VALUE\ ADDED_{it} = \alpha + \beta_1 LnCAPITAL\ PER\ MANUFACTURING\ WORKER_{it} + \delta_j + \gamma_t + \varepsilon_{it}$$

Table 6.1: Manufacturing in US counties, descriptive statistics 1840-1900

		1840	1850	1860	1870	1880	1890	1900
Manu. Capital-Labour Ratio (1900$)	Mean	295	408	678	484	810	1,032	1,931
	S.D.	1,124	283	467	374	709	646	1,171
Manu. Machinery-Labour Ratio (1900$)							360	653
							239	477
Manu. Labour Productivity (1900$)	Mean	739	936	869	758	966	794	1,091
	S.D.	4,912	668	574	425	571	443	557
Manu. Wages (1900$)	Mean			233	149	205	322	359
	S.D.			88	93	99	126	128
Manu. Unit Labour Costs	Mean			0.31	0.21	0.23	0.43	0.36
	S.D.			0.12	0.10	0.09	0.10	0.12
Manu. ULC/Capital Costs	Mean			2.15	1.13	1.85	4.86	
	S.D.			0.77	0.55	0.74	1.19	
Population	Mean	13,514	14,682	15,603	16,945	19,933	22,727	26,040
	S.D.	17,858	23,574	29,663	35,139	42,528	55,211	72,311
Share of Population in Cities	Mean	0.005		0.010	0.013	0.018	0.026	0.032
	S.D.	0.065		0.085	0.093	0.110	0.132	0.146
Manufacturing Workers	Mean	629	603	634	905	1,048	1,707	1,816
	S.D.	1,971	3,245	3,825	5,088	7,339	11,378	11,361
No. of Counties Covered		1,045	1,304	1,639	2,040	2,093	2,491	2,723
Raw Materials Deflator		202.0	158.1	179.1	283.0	179.1	126.8	100.0
Output Deflator		114.0	115.2	123.7	157.7	117.8	105.3	100.0
Capital Materials Deflator		184.3	167.4	156.9	197.3	149.2	117.3	100.0

where δ_j and γ_t are county and year fixed-effects respectively and where in the first regression t = 1890 and 1900 and in the second t = 1870, 1880, 1890 and 1900. I exclude counties for which the census surveyed the activity of fewer than 10 manufacturing workers in any of the years upon which estimation is based to reduce the impact of very small sample sizes by county.

To estimate the effect of the cost of manufacturing labour relative to capital on the rate of accumulation of capital per manufacturing worker (Implication 2), I first calculate a measure of manufacturing unit labour costs by county-decade. This is total annual manufacturing wages in county *i* and year *t* divided by total manufacturing value-added in county *i* and year *t*. It is important to adjust wages for relative productivity levels in this way, since the appropriate measure of the cost of labour in Allen's theory is the cost per unit of labour's output as opposed to per unit of labour's time.

Next, I construct a measure of the cost of capital in county *i* year *t*, which follows an aggregate time series measure constructed by Allen (Allen 2014). This is the product of the capital deflator in county *i* year *t*, as discussed above, multiplied by a measure of the average annualised short-term interest rate in the region containing county *i* during year *t* to year *t+9* minus an assumed capital depreciation rate of 5%. Interest rates are taken from Lance Davis (1965), who calculated estimates of short-term interest rates on bank loans annually between 1869 and 1914 for six regions covering the entire US[86].

Using these measures of manufacturing unit labour and capital costs, I construct a log ratio of the cost of manufacturing labour to capital for each county *i,* year *t.* I estimate the effect of this log ratio in year *t* on the subsequent 10-year change in the log manufacturing capital-labour ratio by regressing the log manufacturing capital-labour ratio on its own 10-year lag and a 10-year lag of the log ratio of the cost of manufacturing labour to capital. The standard *within* estimator of this relationship is subject to the 'Nickell bias' (Nickell 1981) due to the endogeneity of the lagged dependent variable. As such, although I implement and report the within estimator, I also implement and report the Arellano-Bond estimator (Arellano Bond 1991), which is widely used to circumvent the above endogeneity problem by estimating the effect in first difference terms as opposed to de-meaned terms (as in the within estimator) and

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86 For year t for each region, I take a simple of average of Davis' reserve city and non-reserve city interest rates for years *t* through *t+9* (Davis 1965, tables 4 and 5).

instrumenting the lagged difference of the dependent variable and any other endogenous variables by further lags of their levels[87]. As such I estimate the following two equations:

$$LnMANUFACTURING\,\frac{CAPITAL}{LABOUR}_{it} = \alpha + \beta_1 LnMANU.\ UNIT\ LABOUR/CAPITAL\ COST_{it\text{-}10} + \beta_2\, LnMANUFACTURING\,\frac{CAPITAL}{LABOUR}_{it\text{-}10} + \beta_3 LnPOPULATION_{it\text{-}10} + \delta_i + \gamma_t + \varepsilon_{it}$$

where the time signature *t-10* represents a one census/10-year lag and δ_i and γ_t represent county and census year fixed-effects. And:

$$\Delta LnMANUFACTURING\,\frac{CAPITAL}{LABOUR}_{it} = \alpha + \beta_1 \Delta LnMANU.\ UNIT\ LABOUR/CAPITAL\ COST_{it\text{-}10} + \beta_2\, \Delta LnMANUFACTURING\,\frac{CAPITAL}{LABOUR}_{it\text{-}10} + \beta_3 \Delta LnPOPULATION_{it\text{-}10} + \gamma_t + \Delta\varepsilon_{it}$$

where the lagged dependent variable – the 10-year lag of the first difference of the log manufacturing capital-labour ratio – is instrumented by all available lags *t-s* of the level of the log manufacturing capital-labour ratio, where $s \geq 30$. For example, for t =1880, the change in the log manufacturing capital-labour ratio between 1870 and 1880 is the dependent variable. The change in the log manufacturing capital-labour ratio between 1860 and 1870 appears on the right-hand side of the model to capture the 'trend' behaviour of the dependent variable and is instrumented in a first stage regression by the log level of the manufacturing capital-labour ratio for years 1840 and 1850 to avoid endogeneity.

To test the effect of the capital-labour ratio on the subsequent rate of labour productivity growth (Implication 3), I estimate the following two equations. First, within-county, using OLS:

[87] See Cameron and Trivedi (2009) for a textbook discussion of the Nickell bias in dynamic panel estimation and the Arellano-Bond estimator.

$$LnMANUFACTURING\ LABOUR\ PROD._{it} = \alpha + \beta_1 LnMANUFACTURING\ \frac{CAPITAL}{LABOUR}_{it} + \beta_2 LnMANUFACTURING\ \frac{CAPITAL}{LABOUR}_{it-10} + \beta_3 LnMANUFACTURING\ LABOUR\ PROD._{it-10} + \beta_4 LnPOPULATION_{it-10} + \delta_i + \gamma_t + \varepsilon_{it}$$

where the time signature *t-10* represents a one census/ten year lag and δ_i and γ_t represent county and census year fixed-effects. To correct for the Nickell bias I also estimate the following model using the Arellano-Bond estimator:

$$\Delta LnMANUFACTURING\ LABOUR\ PROD._{it} = \alpha + \beta_1 \Delta LnMANUFACTURING\ \frac{CAPITAL}{LABOUR}_{it} + \beta_2 \Delta LnMANUFACTURING\ \frac{CAPITAL}{LABOUR}_{it-10} + \beta_3 \Delta LnMANUFACTURING\ LABOUR\ PROD._{it-10} + \beta_4 \Delta LnPOPULATION_{it-10} + \gamma_t + \Delta\varepsilon_{it}$$

where, once again, the lagged dependent variable – the 10-year lag of the first difference of log manufacturing labour productivity – is instrumented by all available lags *t-s* of the level of log manufacturing labour productivity, where $s \geq 30$.

Finally, to test whether innovative effort was greater where potential returns were higher (Implication 4), I estimate the effect on a county-level count of manufacturing patents of a county-level measure of market access and the county-level manufacturing wage (controlling for manufacturing labour productivity[88]). I control for general supply capabilities in the form of manufacturing labour productivity, the size of the manufacturing labour force, population and the manufacturing capital labour ratio. Finally, I include state dummies so that estimation is based on the within-state effect, which reduces omitted variable bias due to state-level heterogeneity. First, I implement estimation using OLS on logged variables:

$$Ln(MANUFACTURING\ PATENTS + 1)_i = \alpha + \beta_1 LnMARKET\ ACCESS_i + \beta_2 LnMANUFACTURING\ WAGE_i + \beta_3 LnMANUFACTURING\ LABOUR\ PROD_i + \beta_4 LnANUFACTURING\ \frac{CAPITAL}{LABOUR}_i + \beta_5 LnLABOUR_i + \beta_6 LnPOPULATION_{it-10} + \delta_j + \varepsilon_i$$

[88] I use wages and control for labour productivity separately rather than using unit labour costs because labour productivity acts as a supply-side control for the patenting rate in its own right. The results are robust to using unit labour costs instead.

where δ_j represents state fixed-effects. And second, using a count data approach in the form of the negative binomial model (as used in chapter 3):

$$MANUFACTURING\ PATENTS_i = exp(\alpha + \beta_1 MARKET\ ACCESS_i + \beta_2 MANUFACTURING\ WAGE_i + \beta_3 MANUFACTURING\ LABOUR\ PROD_i + \beta_4 MANUFACTURING\ \frac{CAPITAL}{LABOUR}_i + \beta_5 LABOUR_i + \beta_6 POPULATION_i) + \delta_j + \varepsilon_i$$

Results and Interpretation

Implication 1

Table 6.2 presents evidence of a labour-saving bias to late nineteenth century US technological change in the manufacturing sector. Within-county, between 1890 and 1900, a 1% positive change in the manufacturing machinery to labour ratio was associated with a -0.2% change (standard error of 0.02%) in labour's income share of manufacturing valued-added. Estimating the effect over the period 1870 to 1900 using the aggregate manufacturing capital to labour ratio as opposed to machinery capital, within-county, a 1% positive change in the ratio of aggregate manufacturing capital to labour was associated with a -0.18% change (standard error of 0.01%) in labour's income share of manufacturing valued-added. These two results present a consistent picture of an overall labour saving bias to technological change in the late nineteenth century US manufacturing sector. Compared to an investigation using aggregate time series, the use of spatially disaggregated estimation and the within-county estimator reduces the likelihood that this result is due to an evolution in the relative bargaining power of capital and labour during the nineteenth century.

Implication 2

Table 6.3 presents evidence of a positive material effect of the ratio of manufacturing labour costs to capital costs on manufacturing capital deepening, which, combined with the findings in table 6.2, is consistent with the Habakkuk-Allen hypothesis that high wages relative to capital costs induced labour saving technological change in the late nineteenth century US manufacturing sector. Based on the within-county estimator, a 1% rise in manufacturing unit labour to capital cost ratio between 1870 and 1900 relative to the national trend was associated with a 0.05% short-run rise in the subsequent 10-year rate of capital deepening (with a standard error of 0.02%). When we correct this estimate of the short-run elasticity for endogeneity bias by using the Arellano Bond instrumental variable estimator, it rises to 0.6 (with a standard error of 0.06). Although both estimates are positive and statistically significant, they are quite far apart. Given potential endogeneity problems associated with the first and standard potential weak instrument problems associated with the second, it seems reasonable to take an average of the two, equal to 0.33.

The long-run elasticity is calculated by summing to infinity the geometric progression of the product of the short-run elasticity and the rate of convergence of the manufacturing capital-labour ratio raised to the power n, where n is the number of periods since the first impact. Based on the standard formula for the infinite sum of a geometric progression, this is equal to the short run elasticity divided by one minus the rate of convergence of the manufacturing capital-labour ratio of -0.2 using the within-county estimator and 0.68 using the IV estimator (as in table 6.3). This gives a long run elasticity of the manufacturing capital labour ratio to the manufacturing unit labour to capital cost ratio of 0.04 based on within estimation, 1.9 based on IV estimation, and an average across the two of around one.

Given these long-run elasticity estimates, roughly how much of the difference in manufacturing capital-labour ratios across counties by 1900 can variation in manufacturing unit labour costs relative to capital costs explain? In 1900, the 75th percentile of the manufacturing capital-labour ratio by county was \$2,316 compared to the 25th percentile of \$1,200, a difference of 93%. In 1870, the 75th percentile of manufacturing unit labour to capital cost ratio was 1.44 compared to the 25th percentile of 0.73, a difference of 97%. The thirty-year elasticity of the capital-labour ratio to the labour/capital cost ratio between 1870 and 1900 is calculated by summing the geometric series described above for n=3, which equals 0.04 based on within estimation and 1.29 based on IV estimation, giving an average of 0.66. Thus, initial differences across counties in manufacturing unit labour costs relative to the cost of capital in 1870 can explain about 64 percentage points (0.66x82%), or 69% of the 93% difference in the manufacturing capital-labour ratio between the 75th and 25th percentile counties in 1900.

Implication 3

Table 6.4 presents evidence of a significant effect of capital deepening on subsequent rates of total factor productivity growth in the US manufacturing sector between 1870 and 1900. The elasticity of 10-year manufacturing total factor productivity growth to the initial manufacturing capital-labour ratio is 0.10 (standard error = 0.02) based on the within county estimator and 0.50 (standard error 0.1) based on the Arellano Bond IV estimator, with an average of 0.30. The long-run elasticity of manufacturing total factor productivity to the manufacturing capital-labour ratio, calculated similarly to the method described above for implication 2, is 0.08 (0.10/1.27) based on within-estimation and 0.40 (0.50/1.25) based on IV estimation, with an average of 0.24.

How much of the cross-county variation in total factor productivity in 1900 can be attributed to variation in past capital-labour ratios from 1870 onwards? To produce an estimate of the spread of total factor productivity across counties in 1900, I take the residuals of a regression of log manufacturing labour productivity on log manufacturing capital per worker across counties in 1900. The manufacturing total factor productivity of the 75th percentile county based on this measure is 44% higher than that of the 25th percentile county. In 1870, the 75th percentile manufacturing capital-labour ratio by county was $571 compared with $287 for the 25th percentile county, or about double, based on 1900 dollars. The average thirty-year elasticity of manufacturing total factor productivity to the manufacturing capital labour ratio, calculated analogously to the thirty-year elasticity in implication 2 above, is 0.08 based on the within estimator and 0.4 based on the IV estimator, or 0.24 on average. As such, cross-county differences in manufacturing capital-labour ratios from 1870 up until 1890 can explain 24 percentage points (0.24*1), or just over half (55%) of the 44% spread in manufacturing total factor productivity between the 75th and 25th percentile counties in 1900.

Implication 4

Table 6.5 suggests that innovative effort in US manufacturing in 1870 was sensitive to profitability. Based on the OLS estimate, the elasticity of manufacturing patenting to market access across county (but within state) is 0.09 with a standard error of 0.04, controlling for the size of the manufacturing sector, manufacturing labour productivity and other factors. The results of the negative binomial model are expressed as semi-elasticities. They imply that a

$1,000,000 increase in market access across counties within states was associated with a 27% increase in patenting (standard error = 2.2%). A one standard deviation increase in market access across counties within states, equal to about $3,000,000, was therefore associated with an 81% increase in manufacturing patenting. The elasticity of manufacturing patenting to the average manufacturing wage across-counties, within-states in 1870 was 0.15 (standard error = 0.05) based on OLS estimation. Based on the negative binomial model, a $100 increase in the manufacturing wage across counties within state was associated with a 50% increase in manufacturing patenting (standard error = 6.5%) and a one standard deviation increase in manufacturing wages across counties within state, equal to $146, was associated with a 73% increase in manufacturing patenting. Manufacturing patenting rates were highly non-linear across counties. The mean was 19 and the standard deviation was 115, while the 25th percentile was 0, median 2, 75th percentile 9, 90th percentile 31 and 99th percentile 305. As such, although the incentives to innovative determined by market access and manufacturing wages had an economically meaningful effect on manufacturing patenting they explain quite a small fraction of the cross-county variation within state.

Conclusion

The results above provide considerable support for Allen's incentives as determinants of the emergence of modern economic growth in late nineteenth century US manufacturing. Technological innovation was labour saving and sensitive to unit labour costs relative to capital costs. Capital deepening led to higher subsequent gains in total factor productivity. Innovative effort was sensitive to profitability. As these results are based on county-level variation within the US, as opposed to national level variation, it is unlikely that they can be explained by institutional variation.

Nevertheless, there remains much unexplained heterogeneity in the rates of modern economic growth in manufacturing across the US in the late nineteenth century, which may have been due to variation in capabilities. Learning-by-doing can plausibly account for just over half of TFP variation across counties. The other half or so may have been due to variation in the capabilities of producers to master and improve new technology and the associated processes of production. Moreover, the proximate effect of learning-by-doing is contingent upon the prior innovative effort and accumulation of capital required to create the opportunity for learning. In turn, this can only be partially explained (around two-thirds) by factor price incentives. The other third may be due to local capabilities to do R&D and adopt new technology. Alongside the results in the previous chapters of this thesis, these results suggest that Crafts' (2011) view of a balance between Allen's incentives for modern economic growth and the capabilities to respond, in which both played a necessary role, is correct.

Table 6.2: Effect of Capital-Labour Ratio on Wage Share of Value Add in Manufacturing, US counties 1870-1900

	(1)	(2)
Data	County-Decade FE 1870-1900 OLS	County-Decade FE 1890-1900 OLS
Dependent Variable:	*Ln Wage Share of V.A.* $_{it}$	*Ln Wage Share of V.A.* $_{it}$
Ln Manufacturing Capital/Labour $_{it}$	-0.176*** (0.0117)	
Ln Manufacturing Machinery/Labour $_{it}$		-0.214*** (0.0152)
County FE	Yes	Yes
Year FE	Yes	Yes
Observations	10,257	4,966
Years	4	2
R^2 (within)	0.549	0.2955

Robust standard errors in parentheses, clustered by county. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6.3: Effect of Unit Labour Costs on Subsequent Capital Deepening in Manufacturing, US counties 1870-1900

	(1)	(2)
Data:	County-Decade FE 1880-1900 OLS	County Decade IV 1880-1900 Arellano-Bond
Dependent Variable:	*Ln Capital/Labour* $_{it}$	*Ln Capital/Labour* $_{it}$
Ln Manu. Labour/Capital Cost Ratio $_{it-10}$	0.0472^{**} (0.0234)	0.607^{***} (0.0243)
Ln Manu. Capital-Labour Ratio $_{it-10}$	-0.191^{***} (0.0176)	0.471^{***} (0.0309)
Ln Population $_{it-10}$	0.0494^{**} (0.0250)	0.379^{***} (0.0326)
County FE	Yes	Yes
Time FE	Yes	Yes
Observations	5,998	4,985
Years	3	3
R^2	0.590	-

Robust standard errors in parentheses, clustered by county, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6.4: Effect of Capital-Labour Ratio on Subsequent Productivity Growth in Manufacturing, US counties 1870-1900

	(1)	(2)
Data:	County-Decade FE 1880-1900 OLS	County Decade IV 1880-1900 Arellano-Bond
Dependent Variable:	*Ln* Labour Productivity $_{it}$	*Ln* Labour Productivity $_{it}$
Ln Manu. Capital-Labour Ratio $_{it}$	0.467*** (0.0209)	0.708*** (0.0670)
Ln Manu. Capital-Labour Ratio $_{it-10}$	0.104*** (0.0189)	0.496*** (0.112)
Ln Manu. Labour Productivity $_{it-10}$	-0.269*** (0.0222)	-0.250*** (0.0637)
Ln Population $_{it-10}$	0.0240 (0.0220)	0.0298 (0.0230)
County FE	Yes	Yes
Time FE	Yes	Yes
Observations	4,227	3,548
Years	3	3
R^2	0.511	-

Robust standard errors in parentheses, clustered by county, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6.5: Determinants of Manufacturing Patenting in US counties in 1870

	(1)	(2)
Data:	County Cross-Section 1870 OLS Within-States	County Cross-Section 1870 Negative Binomial Within-States
Dependent Variable:	*Ln Manufacturing Patents $_i$*	*Manufacturing Patents $_i$*
(Ln) Market Access $_i$	0.0853**	0.000278***
	(0.0412)	(0.0000227)
(Ln) Manu. Wage $_i$	0.148***	0.00508***
	(0.0414)	(0.000655)
(Ln) Manu. Labour Productivity $_i$	0.0697	-0.000251*
	(0.0719)	(0.000128)
(Ln) Manu. Capital-Labour Ratio $_i$	0.0549	0.00000749
	(0.0470)	(0.000143)
(Ln) Manu. Labour $_i$	0.279***	-0.000126***
	(0.0252)	(0.0000431)
(Ln) Population $_i$	0.651***	0.0000379***
	(0.0551)	(0.00000932)
State FE	Yes	Yes
Observations	1,795	1,895
R^2	0.811	

All regressors log-transformed in equation 1, un-transformed in equation 2.
Robust standard errors in parentheses, clustered by states, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Conclusion

Access to Knowledge in the Twenty-First Century

During the past two centuries, modern economic growth – characterized by rapid and sustained technological innovation – has delivered a far greater rate of increase in living standards than any prior growth regime. This thesis argues that this era of improvement was ushered in by the blossoming of Britain's infrastructure of Knowledge Access Institutions (KAIs) during the eighteenth and early nineteenth centuries, which raised the productivity of R&D and drew an unprecedented proportion of Britain's economic resources into innovative activities. In doing so, Britain's KAIs provided the impetus for the innovation institutions created during the twentieth century, which raised the productivity and supply of innovative effort further still and helped to sustain rapid innovation up until the present day.

However, the prospects for innovation and further improvements in living standards henceforth are contentious. Robert Gordon argues that in the coming decades innovation faces 'headwinds' that may slow it down to its pre-Industrial Revolution rate of advance (Gordon 2016). Gordon points to a deceleration of trend productivity growth in the US in recent decades (Fernald 2014), suggesting that the tide may have already turned.[89]

The innovation infrastructure is far from the only factor that bears on the rate of long run economic growth. Nevertheless, it may contribute to a slowdown if it becomes less effective as the economy moves from one technological era to the next. Productivity growth slowed markedly in Britain in the decades following the British Industrial Revolution, even as it accelerated in the United States, Germany and elsewhere. The Second Industrial Revolution in the late nineteenth and early twentieth centuries was associated with the dawn of the age of sophisticated science and large-scale manufacturing. Perhaps Britain's KAIs were ill-equipped to facilitate R&D in this environment given their relatively low levels of funding and generalist focus, in contrast to the better financed and specialized research departments that were

[89] However, the measurement of productivity growth may have become less accurate in recent years. Furthermore, the relationship between productivity growth and consumer surplus may have become less stable, reducing the usefulness of productivity as a proxy for living standards (Bean 2016).

emerging in universities, large firms and government (Mowery 1990). Furthermore, the productivity of any innovation infrastructure is dependent upon the human capital of those who use it. Perhaps Britain's delay during the nineteenth century compared to the United States and Germany in building an educational system befitting the era of modern science hindered British growth during the Second Industrial Revolution (Lindert 2004, Hanushek and Woesmann 2015).[90] Likewise, we should not take it for granted that the institutions for innovation and education forged in the twentieth century will prove adequate to enable us to achieve our economic potential in the twenty-first century. Nor, as was stressed in chapter four, should we assume that market incentives alone will induce the invention and adoption of the most socially beneficial technologies.

Even so, the findings in this thesis suggest that Gordon may be too pessimistic. Britain's KAIs influenced innovation during the eighteenth and nineteenth centuries by lowering the cost of access to knowledge and promoting the scientific method within the R&D process. Today, the rapidly falling costs of collecting and using data amount to a significant tailwind at our backs. The increasing application of data to R&D, learning-by-doing and the potential for automating processes in sectors such as health care, manufacturing and transportation presents the prospect of major improvements in productivity and living standards in the coming decades (Brynjolfsson & McAfee 2014). Furthermore, it is the world's rate of R&D that matters, not that of any one country, not even the technological leader. The marginal impact of twenty-first century computing and communication devices on knowledge access costs in the developing world is likely to be very large, raising the productivity of innovative effort there and potentially drawing many more people into the collective innovative process.

As such, the main policy prescription arising from this thesis is that rather than focus our concern too narrowly on Gordon's prediction of stagnation we must also dedicate our efforts to guarding against a competing dystopia. This is the risk that technological change in the twenty-first century will occur so rapidly that we will find it quite painful to adapt to it. We must be alert to the possibility that technological change may eradicate jobs at too fast a rate (Brynjolfsson & McAfee 2011) and produce intolerable levels of economic inequality (Piketty 2013). We must also try to understand the potentially harmful psychological and societal

[90] Whether Britain's innovation and educational institutions failed during the Second Industrial Revolution, contributing to Britain's relative economic decline from the late nineteenth century onwards, is a question that requires further study.

effects of the use of new technologies (Bauman & Rivers 2015). Moreover, we must guard against the increasing capabilities of technology to produce mass suffering and destruction (Bostrom 2014). These may prove to be the biggest challenges of the twenty-first century.

Yet the spirit of the European Enlightenment, which was present in the lecture rooms and on the bookshelves of Britain's eighteenth and nineteenth century Knowledge Access Institutions, was optimistic regarding the possibilities for the improvement in the quality of life: an historic example of the principle of 'mind over matter'. Over time, this optimism proved to be justified and, to a degree, it was self-fulfilling. Such an outlook during the twenty-first century would help us make our own luck.

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